JOURNAL OF APPLIED PHYSICS

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Mobilization of Scientific Resources. III

RECENT bills introduced into Congress have proposed a drastic reorganization of the scientific agencies concerned with the war effort. In an attempt to show the extent of mobilization which has already taken place, this issue of the Journal presents a description of the leading wartime civilian scientific organizations. Limitations of time and space have not permitted the inclusion of the scientific laboratories and bureaus attached to the armed services. It is hoped that these may be presented in future issues. Likewise, it has been impossible to include the Joint Committee on New Weapons and Equipment which is charged with the correlation of the research programs of the civilian agencies with those of the Army and Navy.

In examining the several existing civilian agencies one becomes quite aware of the fact that far from being disorganized and unrelated as has been often intimated, these agencies are set up in a strictly logical manner and their functions are well coordinated. The earliest and most general of these agencies is the National Academy of Sciences. It is essentially an honorary society of the most distinguished scientists of this country. It has served as a reservoir of highly competent men who have given unselfishly of their experience, time, and energy to mobilize the scientific talent of the country on an unprecedented scale. To bring the younger and somewhat more active scientists into the preliminary phases of this mobilization the committees of the National Research Council have been invaluable. A complete mobilization would not have been possible without a comprehensive index of the scientific talent of the country. To fill this need the National Roster of Scientific and Specialized Personnel was organized in July, 1940. To assure adequate review and disposition of the large number of ideas and inventions that are always stimulated by war effort, particularly among laymen, the National Inventors' Council was established in August of the same year.

Besides these groups which have helped to organize the scientific talent, three others are described which carry on the war research, most of which is done by contracts with existing university and industrial laboratories. The research and development directed toward better instruments and instrumentalities of warfare, excluding those concerned with aircraft development, is carried on by the Office of Scientific Research and Development. Research and development applied to raw materials and industrial processes is under the cognizance of the Office of Production Research and Development. And finally, for aircraft research and development there is the National Advisory Committee for Aeronautics which was organized in 1915 shortly before our entrance into the first World War.

Thus with this brief review of the wartime scientific agencies which are described in detail in the following articles it is hoped that the general pattern of the organization of the agencies will become apparent and that the reader will be reassured that the scientific "front" is progressing in as orderly a fashion as the military fronts.

National Academy of Sciences

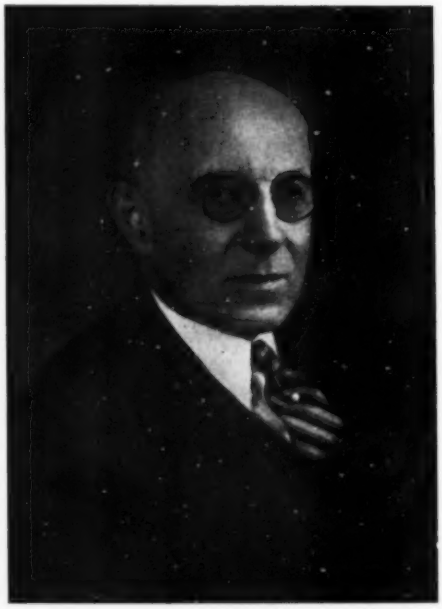
"If you want to get a thing done, don't give people police authority to do it—make them so distinguished that nobody dares run counter to their advice."
—FRANK B. JEWETT

THE National Academy of Sciences originated out of the need of the Government for technical scientific advice in connection with carrying on the Civil War. On March 30, 1863 President Lincoln signed an Act of Congress creating this advisory body. The original members, limited to fifty, were appointed by Lincoln in the charter and were given power to fill vacancies by the election of new members. The organization was patterned after the British Royal Society and was given complete control over its own activities. The charter stated explicitly that "the Academy shall receive no compensation whatsoever for any services to the Government of the United States." This provision was made to keep it unbiased by never letting it fall under the control of any body holding funds for its compensation. The actual out-of-pocket expenditure involved in carrying on a piece of research could be reimbursed but there were to be no regular appropriations.

After a few years, Congress amended the original Act, so as to permit the Academy to determine its own size. The present limit is 450 members although there are fewer than 350. The qualifications for election, according to Dr. Frank B. Jewett, are the highest in the world and membership is a distinction much sought after by American scientists. The officers at present are: DR. FRANK B. JEWETT, *President;* DR. ISAIAH BOWMAN, *Vice President;* DR. L. J. HENDERSON, *Foreign Secretary;* DR. F. E. WRIGHT, *Home Secretary;* and DR. JEROME C. HUNSAKER, *Treasurer.*

When the first World War broke out, there was such a tremendous volume of war research referred to the Academy by the War Department and Navy that the need for extra help became pressing. Consequently, the Academy established the National Research Council made up partly of members of the Academy and partly of non-members, to assist with its work. The two organizations formed a science and research advisory division for agencies of the United States Government during the war.

The original plan was to set up the National Research Council as a temporary agency for the duration of the first World War. However in 1918, President Wilson, after conferring with the Academy, established the Council by an Executive Order as a permanent agency, to advise the Army and Navy as well as civilian departments of the government.



Greystone-Stoller Corp.
Dr. Frank B. Jewett, President of the National Academy of Sciences.

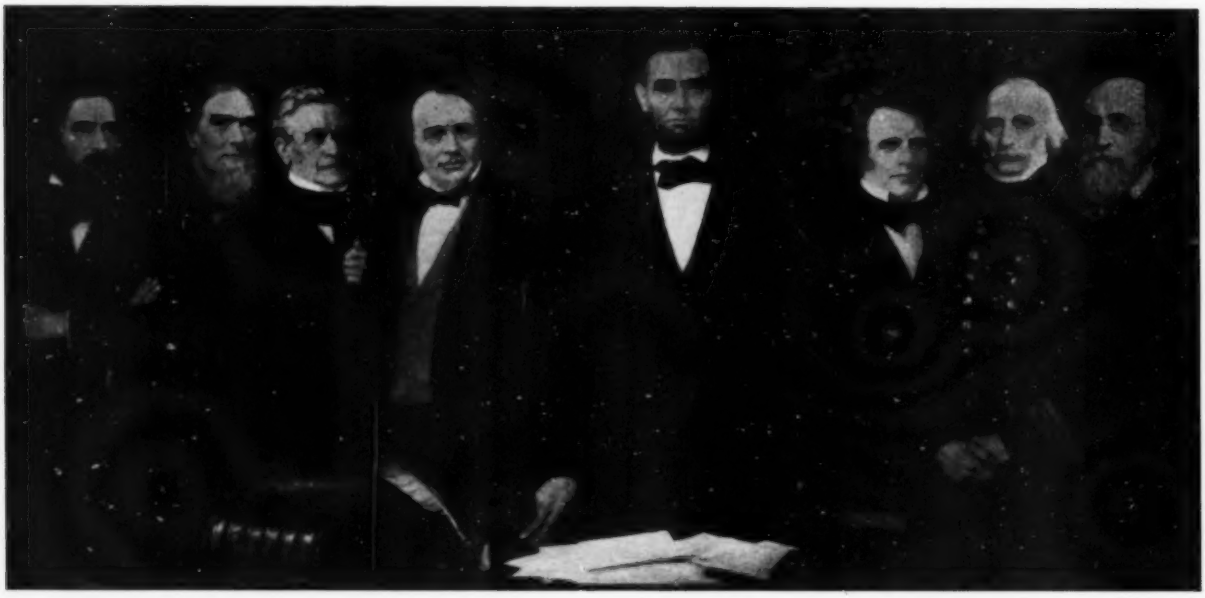
The charter given by President Lincoln still governs the Academy (including its National Research Council), stipulating that members serve whenever requested and that they do so without remuneration. In accordance with provisions in its act of incorporation, the Academy presents its annual report to the President of the Senate. The Academy has no power to tell the Government how to use the advice it gives. However, it actually is used most effectively, for to quote Dr. Jewett, "It is an age-old truism that the strongest authority you can give to

Permanent Home of the National Academy of Sciences and the National Research Council.

anybody is the authority of distinction without power."

When the second World War broke out many people besides Academy members and members of the National Research Council realized that much scientific research was again needed by our War and Navy departments because of the nature of the weapons of modern warfare. Some people thought that the scientific effort behind the war should again be organized under the Academy and the National Research Council. The problem was discussed by Drs. F. B. Jewett, V. Bush, K. T. Compton, J. B. Conant, and one or two other members of the Academy, and the conclusion reached was that under their charter the National Academy and its Research Council could not work swiftly and effectively because of the need for the initiation of research and development work beyond specific requests for advice from government agencies, and the need to engage in work of such magnitude as to require the direct disbursement of government money. That would require a change in the charter. Such a change would make the Academy an executive organization which would destroy the very purpose for which it was created by Congress, because it would then become just another agency of the Government. The decision reached was that a civilian research agency be set up in the executive department for the duration of the war, which could be given money to work on new "instruments and instrumentalities of war" which was the principal problem.

The ultimate result of the discussion held by these few Academy members was the creation by an Executive Order of the National Defense Research Committee with Dr. Vannevar Bush as Chairman. (Later, on June 28, 1941, the Office of Scientific Research and Development was created in the Office for Emergency Management and NDRC was put under OSRD. Dr. Bush was made director of OSRD and Dr. Conant became chairman of NDRC.) With the exception of the Commissioner of Patents and



Founders of the National Academy of Sciences. Left to right: W. B. Patterson, A. D. Bache, Joseph Henry, Louis Agassiz, Abraham Lincoln, Senator Henry Wilson, Admiral Charles H. Davis, and B. A. Gould.

the representatives of the Army and Navy, all the members of the National Defense Research Committee are members of the National Academy.

OPERATION OF THE ACADEMY

Often questions which Government agencies ask on scientific and technical matters can be readily answered by the members of the Academy themselves. Sometimes they require outside help. Indirectly much of the work being done for various departments of the Government has been initiated by ideas conveyed informally to them and which later come back as formal requests that the work be undertaken for the departments. Then the department and the Research Council enter into a contract.

So many technical problems have arisen in the past few years that much the greater part of all the work which is done upon Governmental request is done by non-members of the Academy who are asked to serve it. Dr. Jewett states that during his presidency no one has refused such a request to serve.

The members of the Academy, being men of eminence in their various fields of science, are excellent judges of the competence of people in their field. Hence, when problems are brought to the Academy its members are easily able to choose the best men to give advice on a particular problem. The Academy's "job is to stand sponsor for the kind of people who are selected to do the kind of work demanded by the Government" according to Dr. Jewett. For instance, if the War Production Board places a problem before the Academy, the latter (either itself or through the Research Council) studies it and recommends whether or not it ought to be worked on, gives an estimate of the probable cost of the work, and recommends the agency which would be the best one with whom to enter into a contract.

In the early days when a department of the Government requested certain advice, and after study and consultation this advice was given, the Academy presented the bill, amounting sometimes to $1000 or $2000 or $10,000 depending on the costs involved. Expenses incurred in connection with the projects such as traveling expenses, living expenses, and clerical hire were paid by the Government.

However, since the establishment of the United States Comptroller General's Office this practice of remuneration has been discouraged and practically all work is now done under a contract drawn up between the agency requesting advice

and the Academy before the work starts. The Academy and the National Research Council still are restricted in their activities to the giving of advice but in times such as this the projects involve the expenditure of between $1,500,000 and $2,000,000 a year. There has been a great increase of overhead expense in connection with the Academy's war activities which is unallocable to any particular project or any particular department of the Government. Congress, in its last two appropriations to OSRD, recognized this fact by authorizing Dr. Bush, as Director of OSRD, to pay the unallocable expenses. Before this, Dr. Jewett was obliged to go to the Carnegie Corporation and other philanthropic organizations to secure money for carrying on the work of the Academy until such a time as the Government would reimburse it.

The advisory committees of the Academy are chosen quite independently by that body. The members may consult with the agency presenting a problem for solution, to see if it has any suggestions as to personnel but the Academy refuses to permit anyone to dictate who shall serve on its committees. When the work is completed, the committee is disbanded, and its report is transmitted to the asking agency. No agency may have access to a report made for another, until the latter gives its consent, because the Academy cannot possibly know to what use the information may be put. All reports are held confidential until released by the asking agency as well as by the source of information. If this were not so, much of the value of the Academy would be destroyed.

The war work being done by some of the Academy committees is of such a secret nature that even the Academy members had to be cleared by the military authorities and the Federal Bureau of Investigation. The names of the committees give no indication of their work at present.

When the National Research Council was formed, the question of housing the Academy, in a style appropriate to its importance to the Government, and its position as a kind of national "home" for science, arose. In 1919 Mr. Elihu Root was instrumental in securing $5,000,000 from the Carnegie Corporation, part of which amount was to be used for the erection of a "monumental structure" for the Academy and the Research Council, while the remainder served as a trust fund. The income from this fund pays for maintenance of the building and grounds and the normal operating costs of the Academy.

The National Academy of Sciences building is teeming with activity at present. Two groups under OSRD whose work must be carried on in close cooperation with the Academy and Council and in close proximity to the Army and Navy headquarters are being housed by the Academy. Both units are headed by Academy members. One is the Medical Committee, of which Dr. A. N. Richards is chairman, and which is working with the Medical Committee of the National Research Council, while the other is a group in NDRC under Dr. Richard C. Tolman.

The officers of the Academy serve without pay but there is a paid Executive Secretary and a small office staff. The Chairman of the National Research Council receives a salary on a part-time basis.

Except for its endowment the only income of the Academy is that obtained from the annual dues of its 350 members, each of whom pays $10 a year for the privilege of serving his country. Half of this amount is spent in publishing the *Proceedings* of the Academy and the remaining $1700 is available for Academy expenses. However, as Dr. Jewett has said, the Academy seeks no appropriation because, by accepting funds from Congress, it would lose its independence and become another executive agency of the Government.

National Research Council

IN April 1916, immediately after the attack on the "Sussex," the National Academy which had dealt actively with military and naval problems during the Civil War, offered its services to the government. President Wilson accepted the offer, and requested the Academy to create a National Research Council, to help the government in organizing the scientific resources of the country. It was organized under the charter of the National Academy of Sciences for the purpose of securing the cooperation of all agencies, governmental, educational, and industrial, in which research facilities were available. The Council was set up for this special work of organizing research and securing cooperation of military and civilian agencies in the solution of military problems.

On May 11, 1918, President Wilson by Executive Order made the National Research Council a permanent organization and called upon it for broad services of a scientific and advisory character. Its duties defined in the Executive Order are as follows:

(1) "In general to stimulate research in the mathematical, physical and biological sciences and in the application of these sciences to engineering, agriculture, medicine and other useful arts.

(2) "To formulate comprehensive projects of research and develop means of utilizing the scientific and technical resources of the country for dealing with these projects.

(3) "To promote cooperation in research at home and abroad; to minimize duplications and to encourage individual initiative.

(4) "To serve as a means of bringing American and foreign investigators into active cooperation with the scientific and technical services of the War and Navy Departments and with those of the civil branches of Government.

(5) "To call attention to the importance of military and industrial research necessary in this war.

(6) "To gather and collate scientific and technical information here and abroad and make it available to accredited persons.

"Representatives of the Government upon nomination of the National Academy will be designated as members of the Council and the heads of departments immediately concerned will continue to cooperate in every way required."

Blackstone Studios

Dr. Ross G. Harrison, Chairman of the National Research Council.

Eight divisions were organized within the National Research Council. They were I. General Relations Division, II. Military Division, III. Engineering Division, IV. Physics, Mathematics, Astronomy, and Geophysics, V. Chemistry and Chemical Technology, VI. Geology and Geography, VII. Medicine and Related Sciences, VIII. Agriculture, Botany, Forestry, Zoology, and Fisheries. There was also a Research information service. These divisions have been increased and altered since, in conformity with the intent and purposes of the Executive Order under which the National Research Council was made permanent. The organization into divisions provides a quick and ready framework for bringing to bear expert opinion or active work on any problems in any scientific field. The chairman of each division gives his full time to promotion of the interests of research in his field and in studying conditions affecting the course of such research.

A recent annual report of the National Research Council contains a very clear definition of what the Council is, and what it is not. It states, "The National Research Council is a cooperative organization of the scientific men of America. Its members include not only scientists and technical men but also business men interested in engineering and industry. The Council is not an institution for the maintenance of scientific laboratories. It is rather an organization which while clearly recognizing the indispensable value of individual investigation, hopes particularly to help to bring together scattered work and workers and to assist in coordinating in some measure, scientific attack in America upon large problems in the fields of scientific inquiry. The Council is perhaps implemented best for service in connection with problems which depend for successful solution upon the cooperation of workers and laboratories within the realm of a single science or in the several realms in which various parts of a composite problem may lie. In most of these activities the function of the Council has been mainly to provide the auspices under which the scientific men of the country may join in the wider promotion of research."

Membership in the National Research Council is composed largely of representatives nominated by about 85 scientific societies and includes representatives of some research organizations, representatives of Government scientific bureaus, and a limited number of members at large. The total number is about 220 in all. About one-third of its members are appointed by the President of the United States after having been recommended by the Academy from various departments of the Government, such as War, Navy, and others. All the rest receive their formal appointments from the President of the National Academy of Sciences.

ACTIVITIES OF THE NATIONAL RESEARCH COUNCIL

During the first World War the Council served the Government as a department of Science and Research of the Council of National Defense and also as a Science and Research Division of the United States Signal Corps. Later it devoted itself to research in general, but it continued its cooperation with the Government scientific bureaus and their activities. During the depression years of 1933, 1934, and 1935, the Council cooperated on special scientific problems of the government through the Science Advisory Board.

Although the work being done by the Committees of the National Research Council and the National Academy of Sciences at present in connection with the war effort is not being made public to any great extent, some indication of the type of work they are doing may be had from the statement that by last August over one hundred reports had been furnished to the War Production Board and its predecessor organizations.

Especially noteworthy has been the work of the Metals and Minerals Advisory Committee which has made over one hundred reports on metals substitution and conservation and on ferrous minerals and ferroalloys and similar subjects.

The range of subjects covered by the Council's Executive Board is apparent in the table of contents of one of its consolidated reports (1919–1932) which lists the following:

Fellowships
Grants in Aid
International Critical Tables
Annual Tables
Chicago "Century of Progress" Exposition
Cooperation with the Bureau of Standards
Concilium Bibliographicum
Central Petroleum Committee
Patent Policy
Scientific Property Rights
Science Service
Scientific Instruments Journal
Industrial Personnel Research
Radio Talks
Abstracts

The Council publishes a series of Reprints and Circulars, Bulletins, and miscellaneous publications.

The administrative expenses of the National Research Council are paid out of the income of the $5,000,000 endowment and building fund given to the Academy and the Research Council by the Carnegie Foundation. The gifts of the Rockefeller Foundation for research fellowships have amounted to almost $4,000,000. The General Education Board has furnished a number of medical fellowships, and Infantile Paralysis Incorporated has furnished funds for carrying on the work of two fellowships related to its own particular field.

National Roster of Scientific and Specialized Personnel*

***"Let us do our allocation of skills on the basis of facts. Let us do it in such a way that we preserve to the maximum degree the welfare of the individual, recognizing that the welfare of the State is predominant in time of war and that the one thing we must do with this human machine we are creating, is to win the war."*—LEONARD CARMICHAEL**

AT a time of national emergency such as the present war, when the armed forces of the nation are being rapidly expanded, it is important for a nation to use its trained personnel wisely. It is the purpose of the National Roster of Scientific and Specialized Personnel to help find the right man for the right job at the high professional levels. Dr. Leonard Carmichael, President of Tufts College, is Director of the Roster.

The plan of the Roster is to secure as complete registration as possible of all specially trained American men and women and "to organize a master list in such a way that any special combination of skills or abilities required for particular emergency needs can be selected quickly and accurately."

As Dr. Leonard Carmichael so vividly expressed the work of the Roster, "Professional manpower may be thought of as glorified blueberry pies. The total number of physicists in America, let us say 7000 of them, are the blueberries in one such pie. The Army wants a certain number—they want the whole pie if they can get it—or the Navy—but the interesting thing is that all the blueberries in the pie are not exactly alike. So we have a problem, and it is one of facts in cutting our pie. How many more pies are going to come? How are you going to divide this pie and is this going to be brought about as a result of directives? It is a question of facts. First of all, it seems to me that you have got to have real facts about individuals, about the total supply, and about the number of people who are coming off the assembly line, that is, from the technical training institutions in the country and you have got to put those facts together if the pie is to be used most wisely for the good of us all."

The Roster lists are not to be thought of as civil service lists of people who are willing to take jobs. What the Roster seeks is a complete registration, and its "basic effort" is conservation and proper utilization of technical skill.

Throughout its work the Roster emphasizes three fundamental ideas: (1) An increase in the efficiency of placement in specialized fields; (2) a continuing evaluation of the needs and supplies of manpower in fields served by the Roster; and (3) the conservation and most effective use of the skills of America's specially trained citizens.

HISTORY OF THE ROSTER

The idea for a roster dates back to World War I when scientific societies like the National Academy of Sciences were assisting the government, and the National Research Council was established by the Academy for special service to the government. However, nothing was done about organizing a roster until the summer of 1940 when the Science Committee of the National Resources Planning Board suggested that that agency set up a "Roster of Scientific and Specialized Personnel" with the cooperation of the United States Civil Service Commission. Under the Employment Stabilization Act of 1933 the National Resources Planning Board was charged with the conservation of natural resources, both physical and human.

"The first official sponsors of the Roster" were Dr. Arthur Flemming of the Civil Service Commission and Dr. Thomas Blaisdell, Jr., Assistant Director of the National Resources Planning Board. In addition to these official sponsors the National Research Council, the Social Science Research Council, the American Council on Education, and the American Council of Learned Societies, all favored the establishment of a

* The Editor is indebted to Dr. Leonard Carmichael, Director of the Roster, for reading the proof of this article and for making several helpful suggestions.

roster and helped to develop its policies and procedures once it was established.

Meetings were held under the auspices of the National Resources Planning Board on June 28 and 29, 1940, at which plans were formulated for the Roster. A formal agreement was drawn up between the United States Civil Service Commission and the National Resources Planning Board.

President Roosevelt approved the plan and the National Resources Planning Board received a directive from the President giving it authority to establish the Roster. It was known then as the National Roster of Scientific and Specialized Personnel of the United States Civil Service Commission, but functioned as a semi-independent agency of the National Resources Planning Board. The first funds for operating it were provided by the Executive Office.

When, on April 18, 1942, the President by Executive Order created the War Manpower Commission under the Office for Emergency Management of the Executive Office of the President, the Roster was transferred to the new Commission with all its personnel and equipment. It was, however, to be maintained as an independent entity within that Commission. Organizationally it is now a division in the Commission's Bureau of Placement. Technically its relationship with the United States Civil Service Commission has been abolished but the Roster still works with this Commission in helping to recruit and place qualified professional personnel in the Federal Service.

REGISTRATION WITH THE ROSTER

In order to contact as many technically trained persons as possible the Roster was widely publicized by means of the press, radio, posters in all first and second class post offices (by virtue of its connection with the Civil Service Commission), and by mail. About two hundred technical societies cooperated by permitting the Roster to use their mailing lists, for the mailing of questionnaires. Although most of those listed are citizens, the Roster also listed many very highly trained non-citizens who are willing and able to be of service to this country. Registration with the Roster is purely voluntary and everyone qualified has had the opportunity of enrolling. Anyone with special scientific or professional qualifications who has not yet registered may do so by writing to the National Roster of Scientific and Specialized Personnel, Washington, D. C., stating his field of specialization. He will then receive appropriate questionnaires to fill out.

The deans of technical schools and colleges have been cooperating with the Roster by supplying it with lists of technically trained students in each graduating class. Women are registered as well as men and it is estimated that most of the technically trained women with full-time jobs have already registered.

The Selective Service System is aiding the Roster in registering men skilled in certain specialized technical fields by returning to the Roster a tear-off blank which each registrant in the draft is expected to fill out along with his occupational questionnaire. If the registrant neglects to send in the questionnaire, the Selective Service System has agreed to contact the man's local board in an effort to get the information. Of about 38,000,000 questionnaires sent out by the Selective Service System to American men between the ages of 20 and 65 years, it is estimated that some five percent will eventually come to the attention of the Roster for coding and listing in its analytical punch-card file.

Dr. Leonard Carmichael, Director of the National Roster of Scientific and Specialized Personnel.

To date over 650,000 individuals have registered with the Roster and the number is increasing steadily. On the basis of census figures, Dr. Carmichael estimates that eventually there may be about 1,000,000 technically trained people registered outside of the medical group.

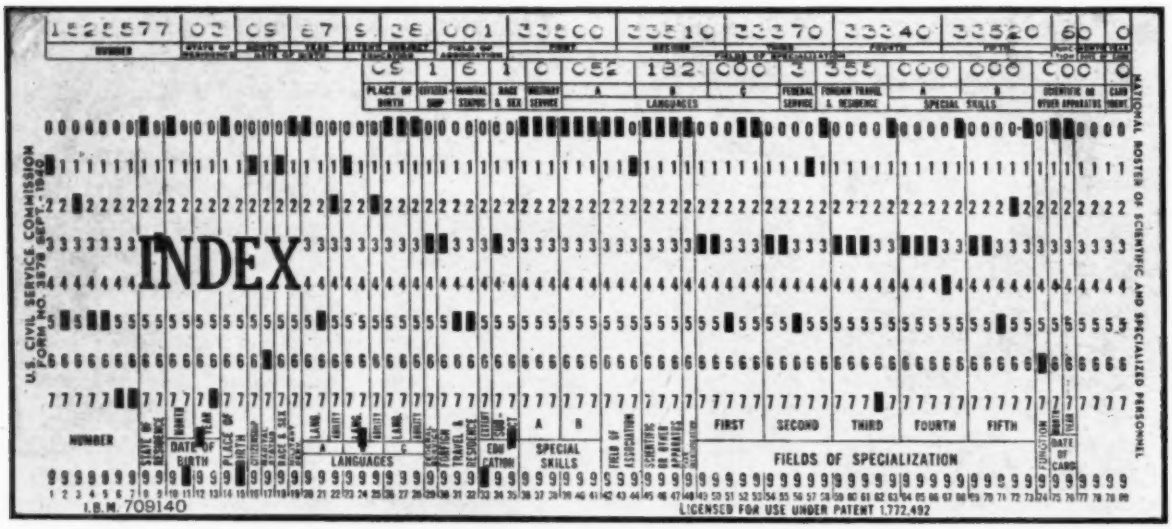
This is difficult to estimate accurately because many wives and members of families tend to upgrade the position of other members of the family in answering the census taker's questions. Another inaccuracy results from the fact that many engineers are listed as executives and managers of industrial firms. These often hesitate to register with the Roster because they feel they have not been active of recent years in the field of their specialized training.

Of the 650,000 names recorded about 230,000 are doctors, dentists, and veterinary physicians, and about 420,000 are non-medical trained citizens. It is estimated that about ½ of the existing scientific and specialized personnel having the qualifications set up by the Roster have not registered, thus far.

The Procurement and Assignment Service of the War Manpower Commission had a complete register of all doctors, dentists, and veterinarian physicians in the country made available to it by the Roster. When Procurement and Assignment was set up as part of the Government, it was decided that the Roster should keep all its records. Now, Procurement and Assignment uses the Roster files in securing doctors, dentists, veterinarians, and sanitary engineers for the Army, Navy, and Public Health Service.

Thus, there is 100 percent registration of medical personnel; probably around 70 percent registration of all the professional engineers in the country; 90 percent of all the physicists, but only 50 percent of the total of all technically trained people. In referring to the above percentages Dr. Carmichael has said, "It seems to be our impression that the more closely organized the scientific field, the better the registration; that is to say, the field in which the standards are the most generally recognized in the profession, is the field in which facts are most easily marshaled, and in which individuals seem to have contributed information to the Roster most adequately."

The Roster has 62 different technical checklists each of which gives a "breakdown" of a



Index card as used by the National Roster of Scientific and Specialized Personnel. On this card columns 1 to 7 indicate alpha-numeric number; 8 to 9, state of residence; 10, 11, month of birth; 12, 13, year of birth; 14, 15, place of birth; 16, citizenship; 17, marital status; 18, race and sex; 19, military service; 20 to 28, languages; 29, federal service; 30–32, foreign travel; 33, extent of education; 34, 35, subject of education; 36 to 41, special skills; 42 to 44, field of association; 45 to 47, service and industry; 48, card identification; 49 to 73, fields of specialization; 74, function. The card shown above is that of a prominent physicist. The punch marks translate as indicated below:

1525577	File identification
03	Massachusetts
09	September
87	1887
09	Ohio
1	Native born citizen of U. S.
6	Married with dependents
1	Male—white
0	No military service
05–18–00	Proficiency in French and German
3	Part time position with defense agency
35	Significant travel experience in Central Europe
9	Ph.D.
38	Chemistry
000–000	Physicist
958	Employed by a college
0	None
33502	Conduction in gases—theoretical
33514	Secondary electron emission—phenomena
33370	Ultra violet methods and effects
33340	Spectroscopy, general
33590	X-ray production
6	Administration

particular field such as engineering, physics, etc. These breakdowns were made by leading civil engineers, electrical engineers, physicists, chemists, etc., specialists in their fields, in cooperation with the Roster staff. The policy of calling in specialists and scientists to help design its methods of operation has contributed greatly to the present effectiveness and value of the Roster.

To aid in arranging alphabetically the punch cards of the more than 1,000,000 people who may be expected ultimately to register with the Roster, a code number is assigned to each name according to the so-called "alpha-numeric" system. This system is based upon the breakdown of a representative alphabetized list such as the census list into 9999 equal segments. In the application of this system to the Roster, each segment is assigned a range of 1000 numbers. The first range starts with 0001000 and the last ends with 9,999,999. The position of the name in the group of 1000 is determined "by guess." Since the Roster will probably ultimately contain a number of names equal to only a little more than one-tenth of the available numbers, there is little likelihood of one's guesses being so far off that all names will not be alphabetically as well as numerically in order.

There are six punch-cards of eighty columns each, for every individual listed, on which all information is indicated by punches of the card. The 3,900,000 cards already contained in the Roster are easily sorted, filed, and counted by machine, and are just as easily located and withdrawn by the machine, when needed for reference.

OPERATION AND USE OF THE ROSTER

According to Dr. Carmichael, the principal use of the Roster is the provision of names of technically trained men and women to the Army, Navy, and to other government agencies doing war work, and through a cooperative arrangement with the United States Employment Service, to private agencies having war contracts. When a request comes in for names of people with a particular skill, every effort is made not to recommend individuals who are at the present time engaged in essential war work if individuals can be found who are engaged in activities that are more or less essential. The Roster has referred over 140,000 individuals listed in its files to the Army and Navy for commissions, to the Civil Service Commission for appointment in federal war agencies, to the United States Employment Service for appointment in defense industries, to educational institutions, and directly to other agencies concerned with war work. The exact number of persons who have secured positions is not known but about 20 percent may be correct. Many more names are certified than there are jobs available because often for personal reasons the individual may not wish to make a change. Each registrant's position is evaluated by specialists in his own field on the basis of information supplied in the questionnaire, so that he will not be asked to change to a less important position than he is in.

The Roster has no power to force an individual to take a position. It can only suggest, and frequently the person lets salary be the deciding factor. Oftentimes, the importance of the work is the deciding factor.

A close relationship between the Roster and private war industry was more difficult to develop than that with agencies of the Government. The Roster operates through the United States Employment Service, but since that service had in the past recruited for labor and skilled jobs, industry had not yet formed the habit of referring to it for filling vacancies in the scientific fields. This condition will probably change in time. Any employer in a war industry who needs personnel in the fields covered by the Roster may apply either to the United States Employment Service or directly to the Roster in Washington.

ORGANIZATIONAL STRUCTURE OF THE ROSTER

To facilitate operations of the Roster, its staff is organized into four principal sections: (1) The Professional Placement and Evaluation Section, (2) The Professional Allocations Section, (3) The Professional Surveys Section, and (4) The Operations Section.

The Professional Placement and Evaluation Section analyzes and evaluates requests for scientific personnel received from government agencies, educational institutions, private industry, the Army and the Navy; evaluates the qualifications of available professional personnel in the light of the requirements of specific requests; and certifies the selective list to the prospective employer. This placement activity is keyed to the total manpower recruiting and placement program of the War Manpower Commission.

Certifications to Federal agencies are made through the United States Civil Service Commission; certifications to industrial establishments are made through the United States Employment Service offices; certifications to the Army and Navy to fill commissions in the armed forces and certifications to fill positions in colleges, universities, and research organizations are made directly. In some instances the Roster will ask consultants in special areas of knowledge to advise it in order to insure greater effectiveness in the utilization and placement of highly specialized manpower.

The Professional Allocations Section was established to meet a specific need in assisting the Army, the Navy, war industries, and governmental agencies to make a proper distribution of our technically trained manpower. This section operates on the principle that while the armed forces of a fighting nation must be constantly absorbing a specific body of men for military purposes, it is also essential to provide for the retention in civilian life of adequate numbers of professional and scientific personnel to perform essential tasks to meet the needs of a nation at war. This section works in close association with the Selective Service System, the Army, the Navy, and war production industries in maintaining their requirements of technically trained personnel. In accomplishing its objectives, evaluations are made of the qualifications of individuals subject to induction in the light of the essentiality of the work they are performing, the need for and the available supply of trained personnel in the particular specialized area, and the "criticalness" of the activity in relation to the war. On the basis of the evaluations thus made, recommendations for deferment are submitted to the local Selective Service Board concerned for consideration in arriving at its classification of the individual.

In those instances where an individual possessing technical or scientific skills is inducted into the armed forces, a statement of his qualifications is submitted to the Office of the Adjutant General, War Department, which statement is used in many instances in effectively assigning the individual to a proper post within the armed services. By a special arrangement with the War Department, in some instances cases of misassignment of specialized personnel in the armed services have been adjusted on the basis of information furnished by the National Roster. As of July 10, 1943, information of this type has been furnished to the Selective Service System in the cases of approximately 11,000 Roster registrants and to the Adjutant General's Office of the War Department in approximately 6300 cases. In addition, the Professional Allocations Section has performed a similar service in the cases of approximately 1900 physicists and mathematicians, 105 engineers, and 381 chemists and chemical engineers.

The Roster's Professional Surveys Section maintains a continuing census of the existing pools, potential supply, and prospective requirements for scientific and specialized personnel in each specialized field of crucial war service. The current information concerning the changing picture of supply and need of professionally trained personnel gathered by this section is used by the Professional Placement and Evaluation Section and the Professional Allocations Section in effectively performing their functions. In making its continued studies of supply of and demand for professional and scientific personnel in the areas of Government, industry, research and education, and the armed forces, this section utilizes various Federal, state, and private fact-finding facilities wherever feasible and conducts direct surveys wherever necessary. Close contact is maintained with the United States Office of Education, the American Council on Education, the Advisory Board of the Engineering, Science, and Management War Training Program, and other similar agencies, and colleges, universities, and technical schools throughout the country relative to prospective graduates and the changing picture regarding teaching, research staffs, and physical facilities in order to relate supply and demand figures to the rate of production. The Professional Surveys Section is also responsible for recommending the list of the "critical" professional fields to the Committee on Essential Activities. In addition, this section frequently makes special studies and reports relating to particular phases of the manpower situation as the necessity arises.

The Operations Section of the Roster performs the clerical operations necessary in effecting registration of the country's scientific and specialized personnel, the coding of their qualifications, machine processing of information and data in the files, and the machine selection of the papers of qualified registrants for consideration by the Placement and Evaluation Section prior to certifying its selective list of qualified registrants to requesting agencies.

It will thus be seen that the Roster has been developed and is today concerned entirely with war work. In its three years of existence, the Roster has "proven itself to be a precision tool which works rapidly and accurately" and a reliable fact-finding source necessary for good judgment in and a thorough understanding of the problems involved in the allocation of skills which faces this nation at war.

It seems increasingly probable that in the period of demobilization after complete victory for the United Nations and in the period of our national post-war development, the services of the Roster will be continuously valuable in readjusting specially trained Americans to a peacetime economy. The tremendous and fully demonstrated advantages of national planning for wartime personnel work in the professional and scientific areas that have been demonstrated by the Roster indicate that in the postwar period America can hardly afford to return to a situation in which personnel placements and educational guidance in the professions are permitted to proceed in the absence of known facts concerning supply and demand in the fields under consideration.

National Inventors' Council

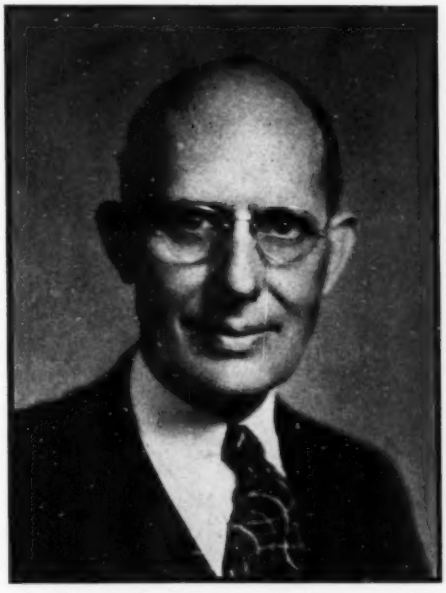
War is a great stimulus to invention. The National Inventors' Council has been established to sift out the useful suggestions and to refer them to the appropriate governmental agencies.

BEFORE the creation of the National Inventors' Council, inventors often lost a great deal of time in trying to interest the Government in their ideas and inventions because they did not know which agency would make use of them, and as a result often sent them to the wrong place. Of all the places chosen by inventors to send their brain-children the one most often selected was the office of the President of the United States, where there is no agency for dealing with them. Inventors tried one bureau or department after another before finding the one which could use their suggestions.

To establish order out of chaos, the Inventors' Council was established by the Secretary of Commerce with the concurrence of the President in August, 1940, as a central clearing house for both the Government and the free-lance inventor, for inventions of a military nature. Its purpose is threefold: (1) to act as a central liaison office between the inventor and the Armed forces; (2) to examine ideas, classify and group them, and select those that appear to have value for the Army and Navy, and (3) to see that they are referred to the right division of the Armed forces.

The Inventors' Council is not trying to make inventions itself as an organization. It merely "sifts" the ideas sent to it and selects those which appear to have value in the national emergency. When first established in 1940, the Council asked for inventions for National defense, but now it is interested only in instruments of war, thus narrowing its field. Originally when ideas for machines for civilian use were received they were referred to the War Production Board if considered interesting. The WPB could then have the idea developed in the industries. Instruments of war were sent to the Army or the Navy for development.

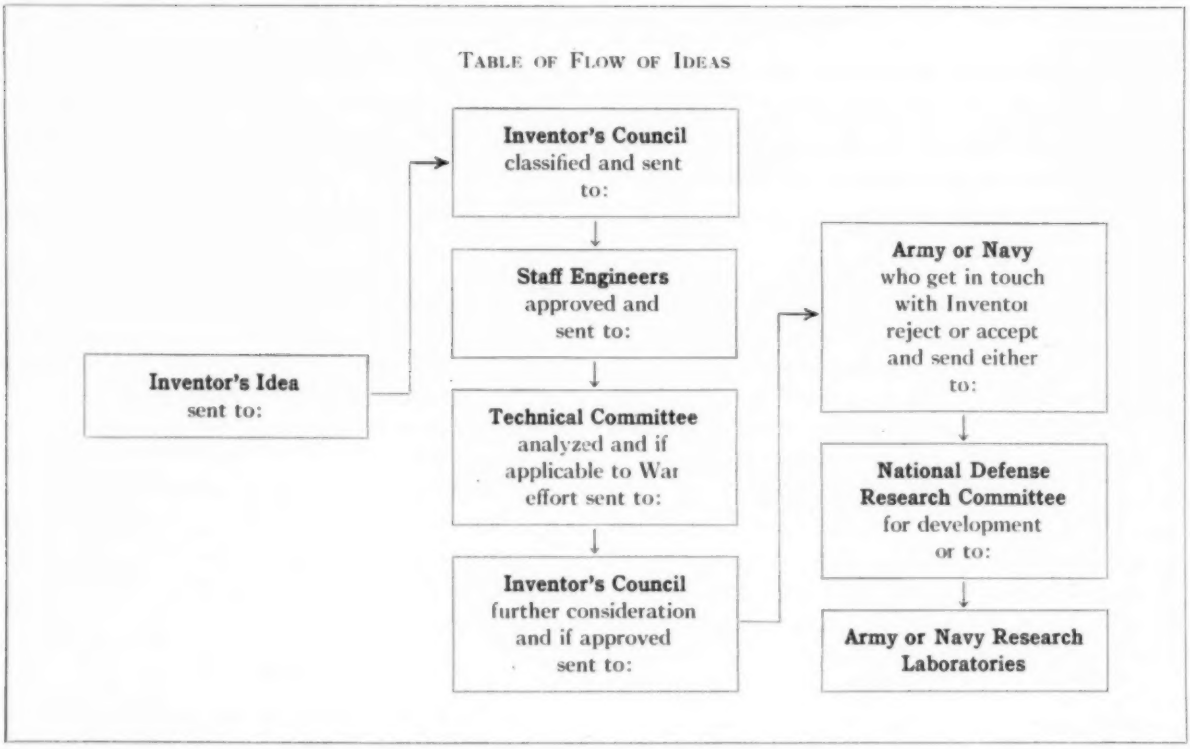
The independent inventor could scarcely know where to turn without referring his ideas to the Inventors' Council because the Army as well as the Navy each has 12 or 14 sections interested in new devices.



Dr. Charles F. Kettering, Chairman of the National Inventors' Council.

ORGANIZATION

The National Inventors' Council whose headquarters are in the Department of Commerce Building, is composed of 15 members with DR. CHARLES F. KETTERING of General Motors Research as chairman; COLONEL L. B. LENT, Chief Engineer of the Council; DR. LAWRENCE LANGNER, Secretary; and MR. T. R. TAYLOR, Director of the Staff of the Council. The Army and Navy each has a representative on the Council and eight other distinguished scientists complete the council membership, all of whom serve without pay. There are about a dozen technical committees, each dealing with inventions in a special field and headed by one of the Council members who is an expert in that field. For instance, there is a committee to examine inventions classed under ordnance and firearms; another for signals and communications; another for aero-



nautics; one for chemicals and chemical warfare, etc.

Assisting the Council is a staff of about 50 persons who help in the work of "sifting" the inventions submitted. About 20 of these men either are engineers or have had some technical training. Besides, it has a contact organization which brings the inventor in touch with the proper group in the Army or Navy in cases where his invention has interested one or the other of them. Here the work of the Inventors' Council ends. From then on, the inventor makes any necessary further arrangements "on his own."

The Council has no laboratory nor funds for developing pilot models. There would be little point in working out an idea to find out whether or not it was successful before learning whether or not the Army or Navy was interested. "Besides," as Dr. Kettering points out, "materials are scarce and time is scarce. It is difficult to get materials for anything outside of immediate demands," (Besides) "you don't want to take anybody off what is absolutely essential work unless the thing is a very important new thing." The Council has not wanted funds for development work because the NDRC was organized for development work in military instrumentalities while the WPB can have the Office of Production Research and Development work on the invention if it is something for civilian use.

FLOW OF IDEAS

When an inventor sends an idea to the Inventors' Council, his communication is acknowledged, classified as to subject, and referred to one or more staff engineers. If it appears to have possibilities, the idea is sent by the staff engineers to the technical committee dealing with that particular field as, ordnance, vehicles, aeronautics, etc. Here the idea is analyzed, and if it seems interesting and is applicable to the war effort, it is referred to the Council as a whole for further consideration. If approved, it is sent to the proper division of the Army or Navy, as Ordnance, Signal Corps, Aircraft, etc., for final acceptance or rejection. If accepted the Council's liaison office puts the Army or Navy in touch with the inventor. The idea may be developed by the National Defense Research Committee or by the Army or Navy research laboratories, after which it is put into production. If the NDRC develops the idea, it is essential that NDRC keep

in touch with the Army or the Navy to insure that the tactical requirements are being met and to aid the Armed forces in developing training procedures for men required to operate and maintain the devices when completed.

RESULTS OBTAINED

By the end of last year, the Inventors' Council had received about 122,000 inventions of which several hundred were found interesting. The rate at which ideas are submitted depends somewhat on war events and upon publicity received by the Council. After Pearl Harbor, the invention rate jumped from 250 items a day to 500 a day, and by the end of January it had reached 750 per day.

On the basis of his experience with General Motors Research, Dr. Kettering believes that the Inventors' Council is getting a higher percentage of useful inventions than General Motors Research obtained from its own new device committee. He regards three to four percent as a very satisfactory fraction of the inventions received. He states that although the total number of workable ideas received may not be divulged, it may be said that out of 120,000 ideas, 1200 have been sent to Army Ordnance. Of this number, work has been started on 41 and 4 were completed by the beginning of this year. Other ideas among the original 1200 may still be workable and may be used at a later time. Because of military secrecy, the fact that an invention may not be used until some future date is not made known. However, the getting of 40 or 45 good inventions out of 1200 is in Dr. Kettering's opinion, "wonderful."

The war agencies of the Government learned from experience during the last World War that they cannot expect amazing new war weapons to come in the mail by the dozens. The War Consulting Board received about 110,000 inventions from the public, of which all but 110 were judged worthless to the war effort on first examination. Only one of the 110 was finally used; a device for testing air-sickness of pilots. The War Department had a similar experience. It received 25,000 inventions of which only 25 were worth considering. Hence the results thus far obtained by the Inventors' Council must be considered gratifying.

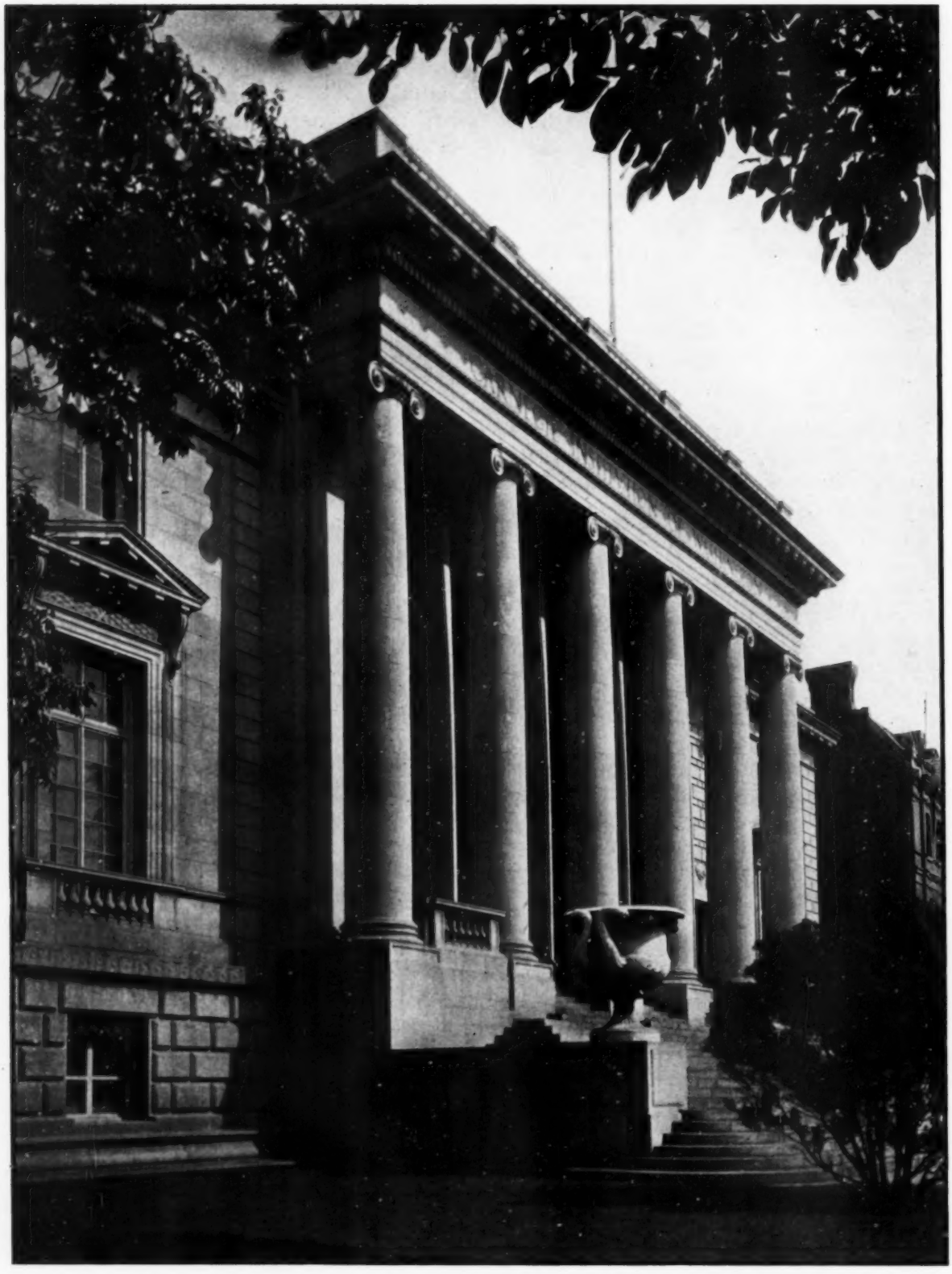
Mr. T. R. Taylor, director of the staff of the Council states that about 40 percent of all the ideas sent to the Council have to do with ordnance: guns, bombs, tanks, and projectiles, and that about 20 percent have to do with aircraft. The remaining 40 percent cover a long list of miscellaneous items ranging from plastics to how to keep soldiers happy in camp.

Thus far several thousand suggestions have been received on how to protect ships from torpedoes. Up to the present time not one has been useful because they usually involve screens which are unmanageable in heavy seas and which cut down the speed and maneuverability of the ship, thus making it even more vulnerable to attack by submarines. During the last war, the Naval Consulting Board received 6740 similar suggestions on protection of ships from torpedoes.

The War Department has made available lists of the types of inventions it wants. One such list includes hydrocarbon vapors as explosives; rocket propelled projectiles; air, centrifugal, and electromagnet guns; automatic mines for land and sea; improved gun- and bomb-sights, optical and otherwise; improved mobile landing field flood lighting; better aircraft brakes, a lubrication system to keep an airplane engine well lubricated during dive operations, etc.

Sometimes a good idea is turned back to the inventor and because of the secrecy surrounding military inventions he can never learn why. As Dr. Kettering explains: "In the case of an emergency, you may get a good invention and still not be able to use it. For instance, a new kind of machine gun. You have started to make a type of machine gun which is quite satisfactory. The new one is an improvement but it is not enough of an improvement to stop the production and retool. . . . That is always a factor especially in an emergency like this where production is so important. . . . It is very much better to get out a good article, than to stop and wait on what might be a somewhat better article."

During the war the free-lance inventor is necessarily groping in the dark as far as military inventions are concerned. However, the number of usable ideas reaching the National Inventors' Council has already exceeded that received during the first World War and demonstrates the effectiveness of the Council in mobilizing free-lance inventors.



Carnegie Institution of Washington, home of the administrative offices of the Office of Scientific Research and Development.

Office of Scientific Research and Development

***"To a democracy, nothing is more important in the conduct of a war than the working out of the smooth relationships between civilian organizations and military organizations in all aspects of the war effort."*—VANNEVAR BUSH**

"TOTAL warfare" has been well named. Military genius is certainly required; but so also is production genius, research genius, and above all good common sense in the blending of these into a working unit. Of this trio, the need for research is often not sufficiently well recognized and yet the loss of life and even the winning of a battle may depend almost entirely upon which side has the most effective weapons. The National Defense Research Committee, which later became a part of the Office of Scientific Research and Development, was organized with the sole purpose of assisting the armed forces by concentrating the scientific talent of the country on the job of producing better weapons for our forces than those in the hands of the enemy.

Although the origin and the operation of the Office of Scientific Research and Development has already been described in several places[1] it seems useful to include a brief description of its activities in this issue along with the description of other scientific agencies mobilized for the war effort. Since these published reports have been made by those who are actually doing the work themselves much use will be made of direct quotations.

"The[2] idea of organizing scientific research on a huge industrial scale, where the ultimate end of 'all out war' was the industry to be served, was slow to emerge. Probably the most difficult hurdle every industry has had to get over in the effective introduction of scientific research as a powerful tool in its operation, has been to realize that the most profitable research is that which is carried on with the least restraint imposed by current practice. Practice can be adapted to radically new ideas, but radical ideas rarely, if ever, evolve from mere improvements in current practice.

"Research in military matters is no exception. War being a very ancient art, military men are on the whole extremely conservative as to new tools. Like doctors, long experience has made them cautious and with possibly a more ordinary tendency to impose on a research project requirements of current practice which, in fact, hamper rather than help. Against this tendency is the fact that they are quick to adopt the radically new once its utility is demonstrated. War more than any other of man's activities puts a high premium on being in the lead.

"As soon as war in Europe on a vast scale was seen to be imminent, the nations there commenced frantically to mobilize and organize their scientific and technical men and resources, and to establish effective liaison between them and the

Dr. Vannevar Bush, Director of the Office of Scientific Research and Development.

[1] V. Bush, J. App. Phys. **12**, 823 (1941); F. B. Jewett, Proc. Int. Rad. Eng. **30**, 113 (1942); K. T. Compton, J. Eng. Ed. **33**, 59 (1942); V. Bush, Elect. Eng. **62**, 96 (1943).

[2] F. B. Jewett, Excerpts from an address, "The Mobilization of Science in National Defense" presented before the Institute of Radio Engineers, January 12, 1942.

combat services. For more than a year after this movement was in full swing across the Atlantic, our aloofness from the struggle and our ardent desire to keep from being sucked into the tragic maelstrom operated to prevent any effective steps in the direction of mobilizing our vast scientific resources for total war. The military services endeavored to strengthen their scientific branches and here and there enlisted the aid of civilian science. They were hampered by inadequate funds, by the pattern of years of a starved organization imposed by an antiwar philosophy, and by the fact that civilian sciences, both fundamental and applied, were built up on a basis of operation in a slow-moving peace economy. The latter had no machinery for marshaling its forces for war and, in the main, it knew little of war's requirements and frequently preferred to follow the courses it understood and liked."

But about three years ago, it became apparent to a few individuals that the laissez-faire approach to the mobilization of science ought to be abandoned in favor of a more direct and forceful organizational approach. At that time there existed certain technical groups and associations which, on the one hand, called for strengthening, and on the other were of suggestive value in the search for a suitable organizational set-up. The scattered technical groups and laboratories within the Army and Navy over the years had been doing commendable work, but had been given insufficient funds and encouragement. It was, of course, obvious that as the tension of the emergency increased, the responsibilities placed upon these technical groups would mount with a resultant need to augment their personnel, but it was equally apparent that they could not be expected to carry the full load of scientific development and adaptation.

"Civilian participation in one way or another in the solution of military problems has come to be taken for granted. It was first given official recognition in the United States when the National Academy of Sciences was incorporated in 1863 by an Act of Congress."

Since then the National Research Council and the National Advisory Committee for Aeronautics had been organized. The NACA, in particular, was especially suitable for wartime activity. Its purpose was clear, it was to "direct and conduct research and experiment in aeronautics." "Throughout its more than twenty-five years of existence, the NACA has given ample testimony of the fruitfulness of co-operation between military and civilian groups, and moreover has provided a prototype as to an organizational arrangement for effecting such cooperative effort successfully."

A somewhat duplicate plan was submitted to President Roosevelt about three years ago for such action as he saw fit to take. The proposal appealed to him and he decided to create the National Defense Research Committee by Executive Order. This Order established the Committee as a division under the Office for Emergency Management and confers upon them power to take the initiative in many scientific matters which they believed to have military significance. It also directed the Committee to develop broad and coordinated plans for the conduct of scientific research in the defense program, in collaboration with the War and Navy Departments; to review existing scientific research programs formulated by these Departments, as well as other agencies of the Government; and advise them with respect to the relationship of their proposed activities to the total research program. Moreover, and this is especially important, the Order directs them to initiate and support scientific research on the mechanisms and devices of warfare with the object of improving present ones and creating new ones.

"It[3] is now nearly three [and a half] years since the scientists and engineers of this country were organized under governmental auspices for the development of new weapons. . . . The initial organization was relatively small, but it has grown to a considerable scale. In June, 1941 a reorganization occurred and the Office of Scientific Research and Development was formed by executive order. The OSRD was given the broad task of co-ordinating the efforts of scientists and technical men in connection with many phases of the war effort, but it was also given the definite charge of pursuing aggressively the work that had already been started by the NDRC: and for this purpose NDRC was incorporated into its

[3] V. Bush, Excerpts from "Research and the War Effort," an address delivered before the American Institute of Electrical Engineers, January 26, 1943.

organization. At the same time OSRD also was charged with the carrying on of medical research which is closely associated with the prosecution of the war, and it does so through the efforts of the Committee on Medical Research which is a part of this organization. . . .

"At the present time the OSRD is making expenditures at the rate of about $100,000,000 a year. In terms of the over-all war cost this is not a large amount of money. It is, however, a substantial sum when considered in terms of research and development. The OSRD operates entirely by contracts with existing academic institutions, industrial organizations, and government agencies. This method is designed to utilize to the utmost available facilities and personnel and to avoid, as far as it can be accomplished, the construction of great new laboratories. About 2,000 contracts for the carrying on of research have now been entered into and of these about 1,400 are currently active. Approximately 200 industrial laboratories and 100 colleges and universities are at work on OSRD projects, and the number of men involved of professional grade is in the neighborhood of 6,000. These men have assistants of various types.

"The way in which the organization functions will be of interest. There is the closest sort of inter-relationship with the Army and Navy at all levels. The NDRC is broken down into 19 major divisions concerned with various phases of war research, and in many cases these in turn are subdivided into sections. Each section is composed of scientists and engineers who are specialists on some phase of the enormous range of war instruments. Working closely with them are officers from the Army and Navy who are also specialists in the field concerned, but who bring in addition the war experience and the contact with tactical reasoning which is essential for sound planning.

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Dr. James Conant, Chairman of the National Defense Research Committee.

"The research projects arise in these sections, usually by reason of round-the-table discussion of the current situation and the needs for improvement. Out of such discussions comes usually a definite request from either the Army or the Navy that the OSRD undertake a development along a certain line. The section is charged with the duty of finding the best laboratory for the conduct of the work and the best personnel to carry it on. After these considerations have been met, the section then recommends a contract for the accomplishment of the work. This recommendation is reviewed by the NDRC, and if the committee approves, it passes the recommendation together with its endorsement to the director, who authorizes the work to proceed.

"The NDRC examines the operations of divisions through the medium of small subcommittees, and by bringing before it the chiefs of the several divisions.

"The manner in which the NDRC operates in this connection is of great importance since it is the central reviewing agency which ties together the entire program. Dr. James Conant, president of Harvard University, is the chairman of NDRC, and its members are as follows: Dr. Roger Adams, head of the department of chemistry of the University of Illinois; Dr. Karl T. Compton, president of the Massachusetts Institute of Technology; Dr. Frank B. Jewett, president of the National Academy of Sciences; Dr. Richard C. Tolman, dean of the graduate school of the California Institute of Technology. These are the men who primarily represent American science and engineering. The Honorable Conway P. Coe, commissioner of patents, is also a member and brings to the committee his wide knowledge of inventions and their appro-

Major General C. C. Williams

Dr. Karl T. Compton

Dr. Richard C. Tolman

Captain Lybrand P. Smith

Dr. Frank B. Jewett

Dr. Roger Adams

The Honorable Conway P. Coe

Members of National Defense Research Committee.

priate handling. The Army is represented by MAJOR GENERAL C. C. WILLIAMS, whose office in the Services of Supply is in touch with developmental work throughout the Army, and is also in touch with the needs of the Army. CAPTAIN LYBRAND P. SMITH represents the Navy Department, where he serves in the Office of the Co-ordinator of Research and Development.

"Once a project has been authorized, the office of the chairman of NDRC is charged with the duty of administering the project from its scientific and technical standpoint. For this purpose the line of authority flows from the director, through the chairman of NDRC, to the divisions, and members of these divisions become the authorized representatives of the office in the guidance of the contractors in their scientific and technical research, in order that their efforts may be directed along the lines that have been approved by NDRC as best adapted to the needs of the services. In this way also adequate reports of progress are made available promptly to the interested parties in the services.

"Since the OSRD is concerned with many broad aspects of the relationship between the military services and the civilian organizations, the director of OSRD also has the benefit of an advisory council, which is representative of many points of view. The council comprises: HARVEY H. BUNDY, special assistant to the secretary of war; REAR ADMIRAL J. A. FURER, co-ordinator of research and development of the Navy; DR. JAMES CONANT, representing the NDRC; DR. A. NEWTON RICHARDS, chairman of the Committee on Medical Research; and DR. J. C. HUNSAKER, chairman of the National Advisory Committee for Aeronautics. It has also recently included in its discussions DR. HARVEY N. DAVIS, director of the Office of Production Research and Development of the War Production Board. By special direction of the President, the director of OSRD has the benefit also of the advice of the president

of the National Academy of Sciences, who joins in many council deliberations. . . . The business affairs, concerned with contracts and the like, are handled by the executive secretary of OSRD, DR. IRVIN STEWART, who also conducts relations with other governmental agencies on financial and legal matters.

"It has been a task of no small magnitude to fit the OSRD into the framework of the government, so it could operate in a smooth and effective fashion. The office is a part of the Office for Emergency Management, which is in the executive office of the President. The OSRD has attempted, and I believe with extraordinary success, to carry on its affairs strictly within the framework as laid down by Congress, and in accordance with the regulations for the conduct of government business with which these various agencies are charged.

"Throughout the rapid growth of OSRD it has had exceedingly effective support from all of the agencies with which it has necessarily come into contact, notably with the Bureau of the Budget, the General Accounting Office, the Civil Service Commission, and many other groups with which it is concerned as an independent agency within the executive office of the President. It is a pleasure to report that in two and one-half years of experience as the head of a new and vigorous government agency, I have never met with anything but the most helpful attitude on the part of the agencies with which I have been called upon to deal, and with the committees of Congress that have had to do with the affairs of the office. This has been in no small degree due to the excellent support of the executive secretary and his office.

"The organization includes also a liaison office, reporting to the director, and charged primarily with the duty of conducting appropriate technical interchange with the allies of the United States. Under specific instructions from the President, there was instituted very early a close interchange with the British on technical matters, and this relationship has continued in a cordial and effective manner. I feel sure that this interchange has expedited the work of scientists and technical men in England in their magnificent efforts for the protection of the British Isles, and I am sure that it has benefited the United States in its war effort. The liaison office, under DR. CARYL P. HASKINS, maintains a London office through which there are contacts with the British Government at all times.

"The close interrelationship of science and engineering is essential in the early aspects of the development of a new weapon. The divisions of NDRC accordingly are made up of men chosen from both fields, working closely in collaboration. Incidentally, these men are selected both from universities and from industry, from large colleges and small colleges, and from private laboratories, and they are drawn from all over the country. Many of them serve without remuneration on a part-time basis; others are on the government payroll, while on leave of absence from their organizations. They serve in every case, of course, as individuals, and they are chosen for their individual qualifications.

"In the introduction of a war weapon into use there is, however, a special problem which is unique and which is not encountered in the same form by industry in the course of its development of new devices. During the course of the introduction of a new weapon it passes from the hands of OSRD directly into the hands of the armed services. OSRD is charged with the research and development, but it is not charged with procurement and use, which are in the hands of the armed services themselves. The armed services themselves directly and through contract carry on a great deal of research and development, and many of their new devices come through this channel. This again I will mention later. However, at the present time I wish to trace the handling of the problem which occurs by reason of the transition of devices from the laboratory into the hands of the military. In order to coordinate this aspect of its work, NDRC maintains two special pieces of organization. One is what is called an engineering panel, made up of engineers who are at the same time members of the various divisions, together with certain other engineers chosen for their over-all grasp. This panel is charged with the duty of seeing to it that appropriate engineering skill is made available to the divisions and sections in an effective way at such time as a new device approaches the period in its development where it begins to be adopted for actual production and use.

"The other special piece of organization is the so-called transition office, which is charged with the responsibility of following the progress of devices, in order to make certain that the problem of scarce and strategic materials is considered in sufficient time. The transition office also arranges with the armed services for initial production in order to carry the device through the transitional phase, in which it has emerged from the laboratory but has not yet appeared in quantity. At this point there is usually involved the production of a sufficient number of pieces of equipment, often produced by hand methods, for purposes of extended tests in the field. There is involved also the selection and indoctrination of an appropriate manufacturer.

"In order to appreciate the way in which the OSRD operates, it is necessary to realize that practically everything it does is highly secret, and that it is not possible to carry on its work under conditions of great secrecy with the same dispatch which is possible when no such conditions obtain. For reasons of security, appointment of personnel in any capacity throughout the organization is made only after careful investigation. A ruling principle, and one which is observed by the Army and the Navy, is that secret matters are held carefully in compartments. This means that no member of the organization will learn of secret matters except to the extent that is necessary for his appropriate functioning in the particular position which he occupies in the organization. Knowledge concerning especially secret matters is restricted to decidedly small groups within OSRD and within the services themselves.

"This leads me to mention one other matter. Ever since this organization was formed, I have encountered the question many times as to why it needs to be organized on a national and vertical basis in accordance with subject matter, and why it cannot be decentralized geographically to obtain the benefit of the many individuals in the country who are highly capable in technical ways, but who must necessarily operate on matters of the war effort in their own localities. The necessity for secrecy and compartmentalization is the reason. In many cities in this country, it would be quite possible to form very strong technical and scientific groups locally, composed of men who would put in part of their time, in the evenings and on week ends, on technical matters connected with the war. These groups could represent many sciences and many types of engineering, and they would be made up of decidedly effective individuals. However, this scheme is not compatible with necessary restrictions on the work of OSRD. It would hardly be possible to assign one subject to each group in a locality. Neither would it be possible to give to such a group the knowledge of the entire range of the development of weapons which would be essential in order to use effectively the diverse characteristics such a group would have. Hence we have felt reluctantly that such groups could not be utilized in the affairs of OSRD. I do feel, however, that they could have real value in other connections, where the conditions of secrecy are not nearly so stringent, and this possibility is being explored.

"On the other hand, while OSRD is organized nationally, drawing its membership from all over the country, its sections are made up of men especially adapted for the problems before them and these men are given full knowledge of the technical and tactical phases of the particular weapons with which they deal. They are kept closely in touch with the progress being made in introducing weapons of this particular type in practice, and they form teams which are able to enlist the services of large numbers of men in many universities and industries for the accomplishment of their purposes. All this is done in such a manner as to keep the secret information as closely confined as is consistent with rapid progress.

"As previously mentioned, not all of the research and development on weapons in this country is carried on by OSRD. It is the duty of OSRD to relieve the armed services as far as possible in this regard, and indeed as the war proceeds and as the officers in the services become more and more burdened with immediate matters concerning the conduct of the war, the load in regard to research and development has shifted quite naturally, so that OSRD is carrying a greater share of the burden. However, both armed services maintain large laboratories in peace and in war for the development of weapons, and they also further development by direct contract with industry.

"The mention of this matter gives me an opportunity to state definitely a fact on which I think there is a great deal of misunderstanding. It has been publicly known for a long time now that when Germany started its all-out air attack on Britain in the summer of 1940, the attack was repelled not only on account of the magnificent equipment and fighting qualities of the Royal Air Force, but also because the British had and effectively used certain radio-warning devices which took the surprise out of the Germans' attacks and assured that their bombers were promptly met by fighter squadrons. It is also known that the British had this device because of the effective work of a group of British scientists and engineers over a considerable period of time. I am also very glad to be able to state that at the same time the Army and Navy of the United States had equally effective devices for this purpose, well developed and in hand. This had been accomplished during years of peace, in spite of the fact that the United States had failed to support its military departments to an extent which rendered research and development in peacetime possible on anywhere near an adequate scale. In particular, I know personally of the early work in this field by a small group of keen naval officers, and there were undoubtedly other groups at work elsewhere. I am looking forward to the day when due tribute can be paid to those officers who very early saw the possibilities of devices of this sort and worked assiduously to the end that they might be practically available. I also wish to emphasize strongly that this work was done long before Europe went to war, still longer before there was any such thing as NDRC. Certainly since its advent, NDRC has worked along these same lines. It has been proud to collaborate with the Army and Navy in so doing, and to work in partnership for the further development of devices on which they had already pioneered, and to share in all of the various possibilities flowing out of that early work. The full story of this development, when it can be told, will involve many scientists and engineers, and its roots go far back for many years. At the present time we are altogether too busy to think much about credit.

"But what of results? In wartime the work of the laboratory is meaningless unless it finds its way into the field of action. The most tangible expression of the success of scientific effort in the present war is to be found in the attitudes of the armed services. Both the Secretary of War and the Secretary of the Navy have indicated to me their satisfaction over what joint efforts have accomplished in terms of operations. At the close of the last fiscal year, the War Department pointed out that it had placed orders amounting to approximately $560,000,000 for items developed by one section alone of the NDRC. As a result of a new process for making an important military material developed by another section, the Army placed orders for plant and product amounting to $270,000,000. In this instance there was an anticipated initial saving of $100,000,000 in plant-construction costs and additional savings of many thousands of dollars a day in operating costs, as compared with previous methods.

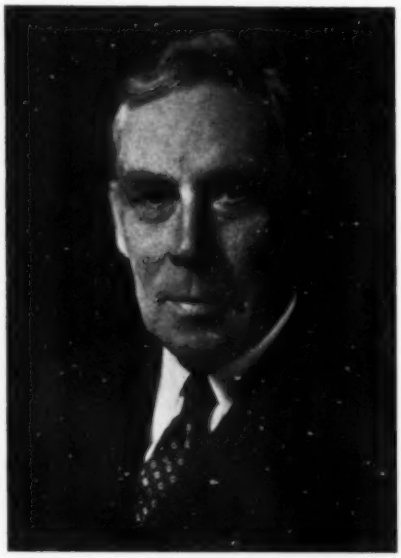
"These figures are now some months old, and a great deal has happened since then. When the story can be told, it will be dramatic, and it will reflect the vigorous efforts of a great group of men, employing the best of teamwork in the common cause. Until then we cannot talk of results. The evidence accumulates rapidly, however, that the devices being developed by American scientists and engineers will play an important part in bringing the war to successful conclusion in a shorter time than might otherwise have been the case."

Office of Production Research and Development

"The job of OPRD is to hasten in every conceivable way the discovery of new technical means and methods of maximizing our output—to do in months for American industry what industry itself might require years or even decades to do under ordinary peacetime conditions. The risks of failure are so high in any one specific case, that private capital cannot be expected to perform all of this kind of development work nor in fact does private enterprise have access to the wide range of both government and non-government research facilities which OPRD is in position to tap."—DONALD M. NELSON

THE entire problem of raw materials and substitutes from which implements of war as well as articles for civilian use should be made, has long been the concern of the War Production Board. In order to facilitate the maximum production of needed critical materials, the WPB set up the Office of Production Research and Development with Dr. Harvey N. Davis, President of Stevens Institute of Technology, as its director. Its field of endeavor includes all materials of industry, both crude and processed, with the exception of synthetic rubber which is the especial province of WPB's Office of Rubber Director.

While the National Defense Research Committee under the Office of Scientific Research and Development is especially charged with the development of instruments and instrumentalities of war, the Office of Production Research and Development is charged with discovering how and from what materials those instruments as well as essential civilian goods shall be made. "In as highly mechanized a war as the one we are engaged in, production is almost as important as combat itself. Any activity that can increase the effectiveness of American production is highly important. One of the ways in which this can be done is through research and development," to quote Dr. Davis.



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Dr. Harvey N. Davis, Director of the Office of Production Research and Development.

The principal functions of the Office of Production Research and Development are:

1. To provide the chairman with technical information on problems with which he is directly concerned and on research and development work in progress in the WPB. The office is also to provide WPB divisions and branches with research information and findings on work which they have in progress.

2. To initiate evaluation and analysis of specific scientific and technological proposals through the establishment of expert committees or through reference to existing research groups in Government education or industry.

3. To get needed research accomplished by contracting with outside laboratories or agencies for experimental work.

4. To bring about development of such projects or processes as are found to merit it, through contracting for the construction of prototypes or the erection of pilot plants.

In order to facilitate the carrying out of its purpose, the OPRD is divided into four branches: (1) Metals and Minerals, (2) Chemical Industries, (3) Consumer Products, and (4) Industrial Processes and Products. Cooperating with OPRD are the Army (QMC, Ordance, Air Forces, and CVS), the Navy (Bureau of Ships), the Board of Economic Warfare, the Petroleum Administrator for War, the

Department of Agriculture, the Bureau of Mines, the Bureau of Standards, the Office of the Rubber Director, the National Academy of Sciences, the National Research Council, the National Defense Research Committee of the Office of Scientific Research and Development, and the National Inventors' Council.

METALS AND MINERALS BRANCH

The Metals and Minerals Branch of OPRD under the direction of Dr. C. K. Leith, Head of the Department of Geology at the University of Wisconsin, has been working on problems such as the following:

1. The introduction into this country of the Pigeon process for producing metallic magnesium, and the carrying on of research to improve it especially in the direction of reducing its consumption of high-alloy steel.
2. The pilot-planting of a number of proposed processes for producing aluminum from domestic bauxites and clays.
3. Research on reclamation of steel scrap and particularly alloy-steel scrap.
4. Research on quartz crystal and mica necessary for radio equipment and formerly obtained from foreign sources.
5. Studies of several phases of the diamond-die and industrial diamond problems.

Cooperating with the Metals and Minerals Branch, is the War Metallurgy Committee of the National Research Council which has prepared well over two hundred technical reports at the request of Dr. Leith.

CHEMICAL INDUSTRIES BRANCH

The main function of the Chemical Industries Branch of OPRD under Dr. Donald B. Keyes, Head of the Department of Chemical Engineering at the University of Illinois, is to evaluate developments and make recommendations concerning the allocation of OPRD funds or the giving of necessary priority by WPB for specific projects. It is assisted by a Referee Board of fourteen distinguished chemical engineers, organized by the Chemicals Division of WPB, and by over one hundred specialists, mostly industrial research directors who can be consulted by letter on any problem.

A common request coming to the Chemical Industries Branch according to Dr. Keyes, "is for the approval of an application for adequate priorities in order to build a pilot plant and try out on a large scale some new chemical process producing a much needed product. The actual importance and need for the product must first be checked and then a thorough investigation must be made to evaluate the process in terms of existing processes or other new ones. Processes that can be applied in existing plants, using idle equipment and requiring very little new and critical material or equipment often receive the highest evaluation for obvious reasons. Requests for these evaluations come largely from the Chemical Division of WPB, but may come from corporations, individuals, and other Government agencies, such as the Defense Plant Corporation, the Smaller War Plants Corporation, and technical groups of the Armed services." The Referee Board meets once a month and prepares opinions on the granting of money and priority to any specific project brought to its attention.

Although many of the problems of the Chemical Industries branch are confidential, the following may be cited as illustrations of its work:

1. When molasses became unavailable for the production of large quantities of alcohol necessary for the synthetic rubber program, the Chemical Industries Branch inspired and correlated the various researches needed to make alcohol production from wheat commercially feasible. It is now pilot-planting processes for making alcohol from ethylene produced from petroleum or natural gas or from wood waste if necessary.
2. It is pilot-planting a process for making glycerine from other materials than waste fats, in order to be ready for any increased demand by the Army for nitroglycerine.
3. It is not only seeking new plastics but also new raw materials for the manufacture of our present plastics. New sources of phenol, formaldehyde, and phthalic anhydride are being sought in this connection.
4. It is carrying on research on the new gasolene additive C-S.
5. It is discovering substitutes for tung oil

used in paints and varnishes for military equipment.

6. It is sponsoring the development of commercial processes for manufacture of acetylene, acetaldehyde, and acetic acid necessary in the chemical warfare, rubber, and textile programs, etc.

CONSUMER PRODUCTS BRANCH

The Consumer Products Branch headed by Mr. Philip N. Youtz, a distinguished architect and engineer, is concerned with research and development in the field of substitutes for critical war materials. Many of its investigations are undertaken at the request of the Conservation Division of the WPB to provide materials for essential civilian as well as military use. A few of the problems under investigation are:

1. Possible substitutes for reinforcing rods for concrete.
2. Substitutes for hemp and sisal fiber.
3. Substitutes for plywood used in packaging.
4. Substitutes for iron and steel pipe in various applications ranging from domestic services to 24-inch oil pipe lines.
5. Various aspects of emergency housing arising out of the creation of new war production centers.

INDUSTRIAL PROCESSES BRANCH

The above three branches, namely, Metals and Minerals, Chemical Industries, and Consumer Products, of OPRD all deal with research and development of materials while the fourth, or Industrial Processes Branch, concerns itself with discovering more efficient ways of producing goods. Until six months ago research and development work of this sort was being done separately by many of WPB operating branches. Now it is being correlated and intensified in the Industrial Processes Branch under the guidance of Professor Paul R. Norton, Jr., Head of the Department of Industrial Engineering at the Virginia Polytechnic Institute.

Research is being carried on on such subjects as:

1. Adaptation of the "lost wax precision casting" method used in the jewelry and dental industries to mass-production of small parts, non-ferrous as well as ferrous.
2. Extension of the use of that technique of fabrication known as powder-metallurgy over a wider field in war production.
3. Development of a process of making laminated heavy ship timbers which may be kiln dried to overcome the shortage of heavy oak timbers caused by the shortage of labor in the woods and the slowness and unsatisfactoriness of kiln drying.
4. Improvement in manufacturing techniques of some items of which from 30 to 70 percent are now rejected as unacceptable.
5. Reduction of the quantity of scrap produced per unit of final product.

The OPRD has 122 research projects under way and another 102 projects under consideration. They are all being carried on in already established governmental or other laboratories through research contracts or by transfer of funds. The OPRD itself maintains no laboratory.

In order to prevent duplication of research or development work going on under the direction of any other governmental agency and to insure that work shall be assigned to the agency best suited to do the work, the OPRD has established cordial informal contacts with a large number of other research agencies in Washington. Mr. Davis stresses the fact that, "the division of field between OPRD and OSRD is in general quite clear to both groups, and that all doubtful or border-line cases are cleared by us with OSRD, and a definite agreement reached as to which can best handle a given problem before we undertake to do anything about it." The OPRD does not "knowingly duplicate research" being done by other government agencies.

National Advisory Committee for Aeronautics*

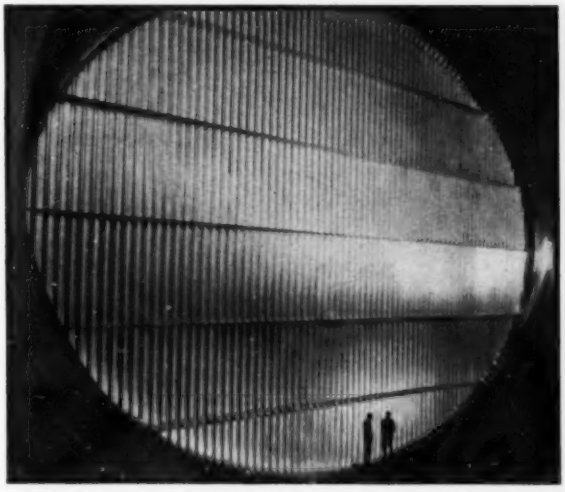
The National Advisory Committee for Aeronautics, once the unwanted child of a skeptical Congress, slipped into being on a rider attached to a Naval appropriation bill, found berth in the offices of the Army Signal Corps, and has emerged long since as a "man of property" and one of the nation's favorite sons.

ALTHOUGH the Wright brothers had demonstrated to the world the practicability of flying in 1903 at Kitty Hawk, North Carolina, the aviation industry took hold very slowly in America. Five years later the government bought its first plane in order to train Army and Navy officers in military flying. Up to the first World War, the meager aircraft industry had only one customer, the United States Government, and it had purchased fewer than 100 planes. There was very little research going on in aeronautics in this country, while in Europe all the leading countries were doing aeronautical research under various governmental agencies. Between 1908 and 1913, Germany had spent $32,000,000 on aeronautics; France, $25,000,000; Russia, $12,000,000; England, $3,000,000 and the United States only $435,000.

In 1913, Dr. Charles D. Walcott, then Secretary of the Smithsonian Institution and a member of the National Academy of Sciences, proposed that an aeronautical research group be organized and that it use Langley's old laboratory in the Smithsonian building. A committee studied the matter, reported favorably, and the Advisory Committee of the Langley Aerodynamical Laboratory was set up. Among the distinguished members present at its first meeting, held on May 23, 1913, were Capt. W. I. Chambers, Glenn Curtiss, Orville Wright, Dr. Walcott, and officers of the Army and Navy. Only three meetings were held when the Comptroller of the Treasury precluded the possibility of governmental aid by ruling that the committee could use no government funds nor personnel because it had not been established by law. So the life of the Advisory Committee of the Langley Aerodynamical Laboratory ended.

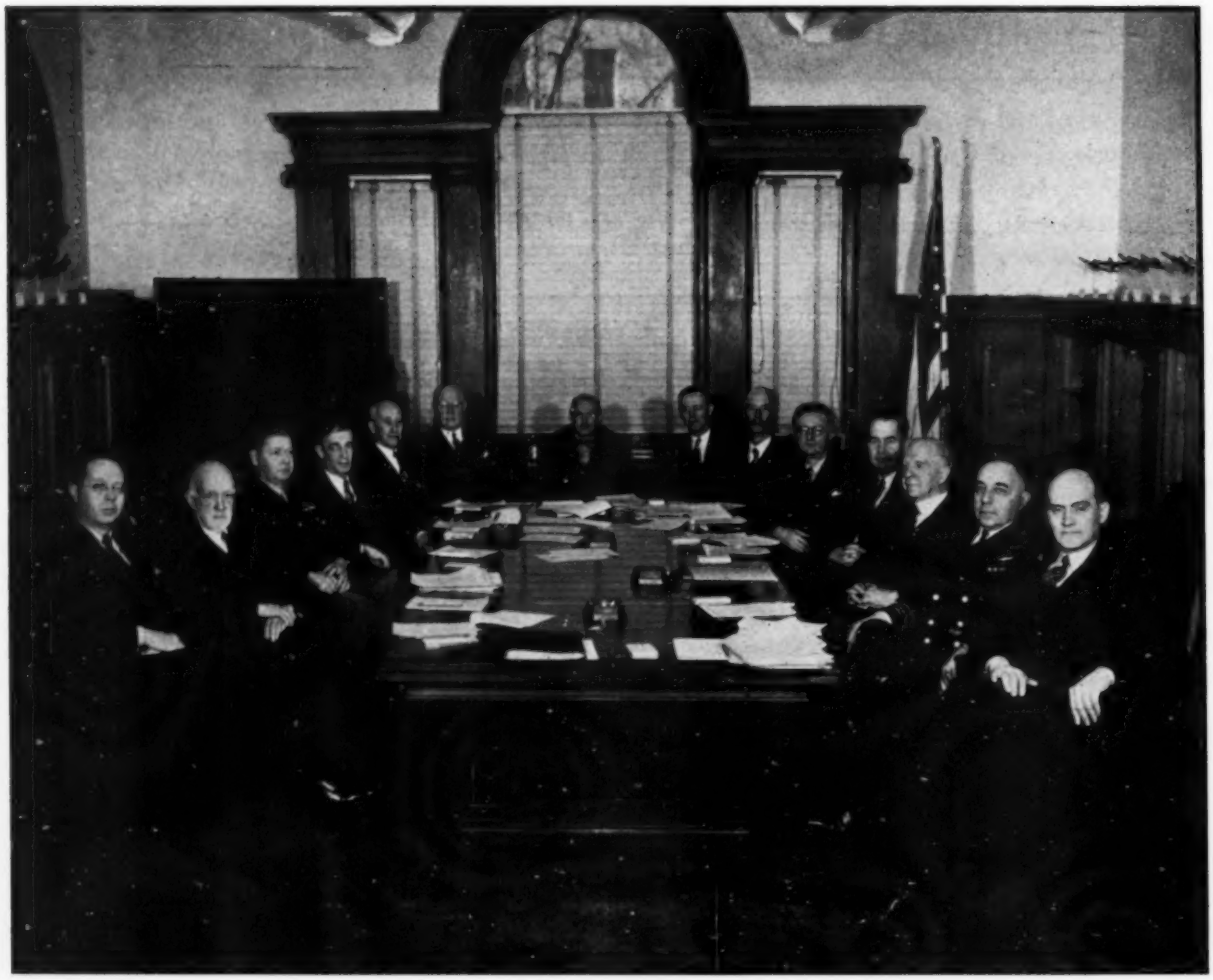
Dr. Walcott was not easily discouraged. Friends of aviation met frequently with Dr. Walcott in his home to discuss means of winning governmental support for their idea. When President Wilson was approached on the subject of establishing an aeronautics committee by law, he refused because he thought it would appear to be a warlike measure and he was trying to keep us out of the European War which had already broken out.

Finally, however, Dr. Walcott succeeded in getting his bill attached as a rider to a Naval appropriation bill, which was passed by Congress and became law March 3, 1915, and the National Advisory Committee for Aeronautics was created —"for the supervision and direction of scientific study of the problems of flight, with a view to their practical solution" and to "direct and conduct research and experiment in aeronautics."



NACA 19-foot pressure wind tunnel, Langley Field, Virginia. View of guide vanes at corner of return passage of the 19-foot pressure wind tunnel.

* The Editor is indebted to Mr. J. F. Victory, Secretary of NACA for reading the manuscript of this article and making several helpful suggestions.



National Advisory Committee for Aeronautics, Meeting, Washington, D. C., December 17, 1942. Left to right: Burden, Durand, Chidlaw (representing Arnold and Echols), Bush, Orville Wright, Lewis, Hunsaker, Victory, Abbot, T. P. Wright, Warner, Briggs, Kraus, Reichelderfer (Admiral McCain and Dr. Mead not present).

Congress, with some misgiving and an abundance of caution, appropriated $5000 a year for five years, or "so much thereof as shall be necessary" for the work of the new Committee. After its first year the Committee began to receive annual appropriations from the Congress, the first of which amounted to almost $85,000. With this a modest start was made in building what has since become the great Langley Memorial Aeronautical Laboratory. Each year the Committee submits a report to the President who transmits it to Congress informing that body of the work accomplished and making recommendations for future work and necessary appropriations. Its appropriation for 1942 was about $20,000,000.

As World War I provided the impetus for the organization of the National Advisory Committee for Aeronautics, so World War II resulted in a tremendous expansion of its research and physical equipment. Secrecy surrounds most of its activities for the present, the results of its research being available only to the Army, Navy, and a few aircraft manufacturers who are working under contract with the Government.

ORGANIZATION AND PERSONNEL

The National Advisory Committee for Aeronautics has the distinction of being not only a main-stay of aviation research but also the one great Government agency controlled by non-

paid civilians. It has a membership of fifteen, appointed by the President and serving in that capacity without compensation. They include two representatives each, from the Army and Navy air organizations and from the Civil Aeronautics Authority; the heads of (1) the Smithsonian Institution, (2) the Weather Bureau, (3) the National Bureau of Standards; and eight members appointed from private life. The original number of twelve was expanded to fifteen in 1929 by amendment of the original act of 1915. Other unpaid personnel are about 160 members of standing sub-committees who are subject to annual reappointment.

The present Chairman of NACA is DR. JEROME C. HUNSAKER, head of the Departments of Mechanical and Aeronautical Engineering at Massachusetts Institute of Technology, while the Director of Aeronautical Research, is DR. GEORGE W. LEWIS, who has been with NACA for twenty-four years and is now in charge of the work of almost 4000 employees.

As presented in the original statement of aims of the NACA it was "to conduct as much research as possible at full scale." Other aims were to study (1) the stability of aircraft by mathematical investigation, (2) the improvement of air speed meters for the prevention of stall, (3) more efficient wing sections, (4) propellers, (5) efficient and economical engines, (6) form of the airplane "toward natural inherent stability," (7) radio telegraphy, which research has now been discontinued, (8) general physical problems such as non-corrosive metals, the generation of hydrogen, etc. Other duties included (1) the writing of research reports, (2) the creation of a standard aeronautical nomenclature, and (3) the compilation of an aeronautical bibliography.

The research is divided under five main headings, assigned to as many permanent committees,

NACA 8-foot high-speed wind tunnel, Langley Field, Virginia. This tunnel is used for research on large-scale models and full-size airplane parts at air speeds from 85 mph to more than 500 mph, especially for compressibility effects. The tunnel is powered with an 8000-horsepower motor which drives an 18-blade 16-foot diameter propeller. The working space inside the dome is at reduced pressures during operation of the tunnel, simulating at full speed an altitude of more than 12,000 feet. The results of research in this tunnel, incorporated in the design of high-speed airplanes, improve aerodynamic efficiency.

which are subordinate to the main committee of NACA. These are (1) aerodynamics, (2) power plants for aircraft, (3) aircraft materials, (4) aircraft structures, and (5) problems of air navigation. Earlier there were two others, aircraft accidents and inventions and designs.

Smoke is used in the NACA smoke tunnel at Langley Field, Virginia, to make the flow of air visible as illustrated in these photographs. Note the smoothness of the air-flow in the lower picture. When the angle of attack has been increased to 10 degrees, the air-flow begins to separate from the upper surface of the airfoil (center view) and when increased to 30 degrees the flow separates completely from the upper surface. Turbulence behind the trailing edge of the airfoil may be observed in this picture.

Since 1917, a large program of research has been carried on at Langley Field near Hampton, Virginia, where the NACA was given land by the War Department on which the Langley Memorial Aeronautical Laboratory has been developed by the NACA.

The first of many novel developments in research equipment was the variable density wind tunnel in which small models could be tested under a pressure of 300 pounds per square inch in order to obtain results approaching the accuracy of full-scale tests. This was soon followed by a wind tunnel large enough for the full-scale testing of air propellers, known as the Propeller Research Tunnel. It had a throat 20 feet in diameter and at the time of its construction was the largest wind tunnel in the world. This tunnel was used also for the testing of airplane models at larger scales. The results were so promising as to lead the Committee to the construction of a full-scale wind tunnel with a throat 60 by 30 feet. This is now the largest wind tunnel in the world, although it will soon be superseded by a much larger tunnel under construction by the NACA at its west coast research laboratory.

Further developments of novel equipment at Langley Field included the "NACA Tank," a basin of salt water 2900 feet long, 25 feet wide, and 12 feet deep. From tests in this tank fundamental data have been derived which have led to great increases in the performance and efficiency of seaplanes. Other novel research equipment at Langley Field includes free-spinning tunnels, a free-flight wind tunnel, several high speed wind tunnels, and a structures research laboratory. Engine research was also conducted at Langley Field until transferred in 1943 to the Committee's third major research station at Cleveland, Ohio.

The results of these researches, after being passed upon by the subcommittees, are published in hundreds of technical memoranda, reports, notes, etc., by the Office of Aeronautical Intelligence, which is that part of the NACA charged with "the collection, classification, compilation, and dissemination of scientific and technical information." During the present war, the distribution of this information has been restricted, but advance confidential reports are issued to the contractors who are building Army and Navy aircraft to keep them informed of the latest tests at NACA laboratories.

The Office of Aeronautical Intelligence acts also as a clearing house for aeronautical information collected in Europe and America for the benefit of our armed forces and of the aviation industry. It helped standardize the vocabulary of aeronautics by publishing pamphlets of aeronautical terms and their definitions entitled "Nomenclature for Aeronautics." These reports have been followed by the publishers of large dictionaries.

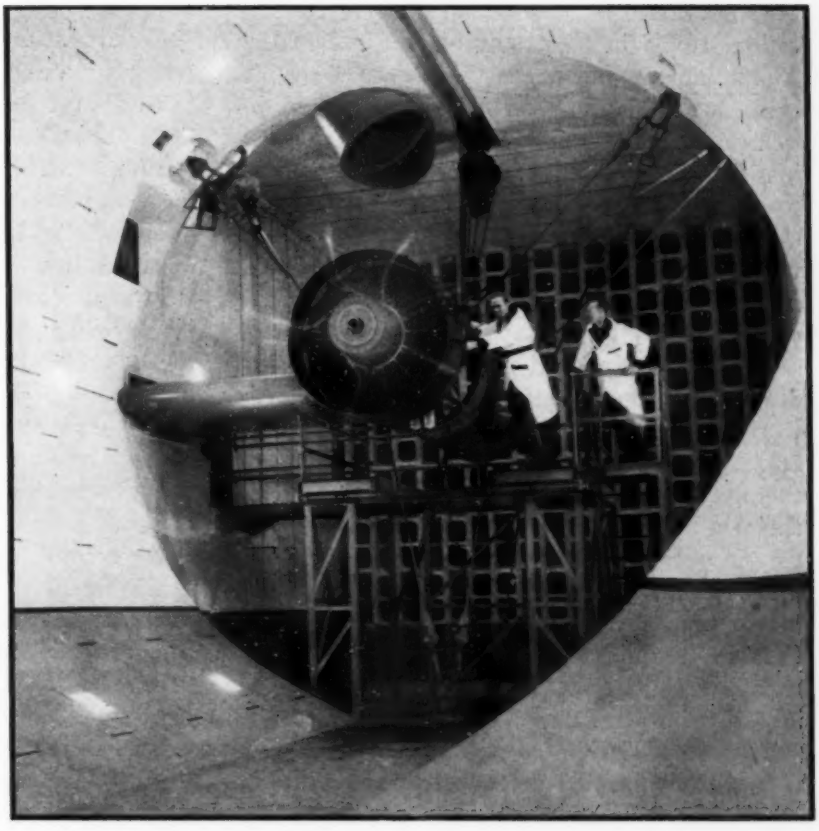
SUBCOMMITTEES OF NACA

Under each of the five main research committees there are numerous standing subcommittees set up to study special subdivisions of the main topic. For instance, the Aerodynamics Committee has standing subcommittees on propellers, vibration and flutter, sea planes, rotating wing aircraft, and vibration of dual-rotation propellers. The Committee on Power Plants for Aircraft has subcommittees on fuels and lubricants, lubrication, friction, supercharger compressors, recovery of power from exhaust gas, wear, induction system de-icing, and heat exchangers. Under Aircraft Materials are one on metals used in aircraft and another on miscellaneous materials and accessories; also a new group set up to study welding problems. The Committee on Aircraft Structures has no standing subcommittee. The Committee on Operating Problems has subcommittees on meteorological problems, lightning hazards, and de-icing problems.

Besides these standing subcommittees, there are numerous special groups formed to solve particular problems, which are disbanded when their work is completed.

Until several years ago, the subcommittee personnel was drawn largely from government agencies but recently the percentage of others serving on them is quite high. The number of civilian consultants from aeronautics and allied industries serving on these subcommittees is now 225. They serve not as representatives of their companies, but as private individuals who have become expert in their field. Recently the NACA has adopted a new policy of appointing these men for a term of only one year to provide a certain turnover and thus insure the securing of new experience and new points of view.

Army and Navy personnel, especially engineering officers, sit on the sub-committees, thus getting first-hand knowledge of civilian expert opinion presented at these meetings. Every phase of aeronautics is discussed. Sometimes members of the WPB attend these meetings to hear of new



NACA Aircraft Engine Research Laboratory, Cleveland Airport, Cleveland, Ohio. Inside the engine-propeller test house.

technical problems which involve a change in production in some other industry supplying aeronautics. The tremendous activity which goes on at these committee meetings usually held in the Committee's Washington headquarters on Dupont Circle has repercussions in many laboratories and industries throughout the country.

Although the work is confidential and much of the information is kept under lock and key, the Army, Navy, and airplane manufacturers working under Government contract are kept informed of the newest, most secret discoveries, if essential to their work.

COORDINATION OF RESEARCH

Since the first year of its existence, the Committee has sought to utilize effectively the facilities and personnel of scientific and educational institutions for the conduct of smaller special investigations for which their facilities were adaptable. Such work was done under research contracts which called for the payment by the Committee to the universities of modest sums for the submission of reports resulting from the investigations requested, and reports were required to be in form suitable for publication. The volume of this activity has been multiplied since the outbreak of the present war. The Committee now has 80 contracts in force with 40 institutions, and the present budget for this work is $500,000 per year.

The Committee maintains a modest staff to visit scientific and educational institutions in order to stimulate their interest in the conduct of research useful to the war program. The same staff also visits aircraft manufacturing plants to discuss their current technical problems, to bring to their attention the results of recent researches applicable to such problems, and to take from them, for the information of the Committee, their suggestions as to problems requiring laboratory investigation by the Committee. This procedure tends not only to prevent unnecessary overlapping and duplication of effort, but also to facilitate quick application of results in order to obtain maximum value from the scientific investigations conducted.

This coordination of research also involves visits by Committee personnel to the Material Division of the Army Air Forces at Wright Field, Dayton, Ohio, to the Naval Aircraft Factory, Philadelphia, to the National Bureau of Standards in Washington, and to the Forest Products Laboratory at Madison, Wisconsin. In addition the Army Air Forces maintains a liaison staff at each of the NACA laboratories and the Navy sends representatives to the laboratories from time to time to keep in close touch with projects in which the Navy is especially interested.

Liason is also maintained with British aviation research committees and with the Canadian National Research Council by exchanging visits. The permanent European office of NACA, opened in Paris in 1919 with its resident representative, has been most likely suspended for the duration.

EXPANSION OF LABORATORIES

Since the beginning of the war in Europe, the work of the National Advisory Committee for Aeronautics has grown by leaps and bounds, and so too has its research equipment. Not only has Langley Field in Virginia been expanded, but two immense new laboratories have been built to carry on research. In February, 1939, President Roosevelt recommended that Congress provide sufficient funds for a second major aeronautical research station. It was authorized by Congress in the Third Deficiency Act, approved August 9, 1939. The site selected was Moffet Field, California, 38 miles south of San Francisco, where construction was immediately begun on a fully equipped flight research laboratory and a group of wind tunnels including a full scale tunnel that would dwarf any others in existence. The laboratory at Moffet Field was named the Ames Aeronautical Laboratory in honor of the late Dr. Joseph S. Ames, who had been a member of NACA from 1915 to his resignation in 1939. The Ames Laboratory "materially augments and strengthens the Committee's facilities for research in aerodynamics." Dr. Ames was the last of the members of the original NACA appointed by President Wilson. He had been chairman of the Executive Committee from 1919 to 1936 and chairman of the Main Committee, 1927–1939, when failing health caused his resignation on October 7, 1939.

A special committee of NACA asked to survey research facilities in 1939, reported a serious lack of aeronautical engine research facilities and

recommended the immediate preparation of plans and estimates for an additional laboratory for engine research.

The Congress in June, 1940 authorized the construction of the world's largest aircraft engine research laboratory located at the Cleveland airport. Research started in May, 1942 and construction of the major engine research units was substantially completed by the end of that year. Various units have been put into operation as the equipment has been installed. This $20,000,000 station also has a flight research laboratory, an altitude wind tunnel in which tests can be conducted under conditions of temperature and density existing at 50,000 feet, and an icing tunnel to study problems of de-icing in flight. The Aircraft Engine Research Laboratory conducts investigations on single- and multi-cylinder engines in order to increase the horsepower output, engine economy, and altitude of operation. It will also work on carburetors, ignition systems, fuel injection systems, and stresses in engine parts.

The attitude of Congress and of the general public has indeed changed since the day in 1915 when "$5,000 or so much thereof as may be necessary" was appropriated for aeronautical research. The NACA need no longer apologetically argue the value in dollars and cents of increased efficiency in aircraft, as it did in its Annual Report for 1935. The daily events of the war have made converts of the most doubting of doubting Thomases.

IN spite of an apparently complete peace-time organization of science in America, it has always been our experience, in the time of great emergency, that it appears advisable to establish temporary new agencies to deal particularly with the emergency. I have frequently tried to analyze the reasons for the establishment of special scientific agencies during times of crisis. They are, I think, varied and rather fundamental. One of them is that every great crisis involves conditions so different from the normal situation that the types of organizations which can survive and operate during peace-time are not adequate to meet the emergency. It may be, for example, that the emergency calls for exercise of very extensive administrative functions, such as the supervision of research projects and the disbursement of large governmental funds to a far greater extent than in peace-time. Hence a peace-time body of scientific men organized primarily to exercise advisory functions may not be organized in the manner suited to prompt and efficient executive action. Another reason is the impossibility of always maintaining in the administrative positions of peace-time agencies the personnel who would be most effective for handling important projects in a war emergency. Men who have the proper capabilities are frequently too busy and too active in other directions to be willing to hold positions in a peace-time organization which is relatively inactive. Consequently when the emergency comes, the only alternatives may be to change the leadership in the existing organizations, a difficult if not impossible process, or to set up new temporary agencies to deal with the emergency.

KARL T. COMPTON in his Pilgrim Trust Lecture as reported in *Nature*, **151**, 601 (1943).

Here and There

FORMATION OF A DIVISION OF ELECTRON AND ION OPTICS IN THE AMERICAN PHYSICAL SOCIETY

The following announcement was made on July 7 by the Secretary of the American Physical Society.

"A Division of Electron and Ion Optics in the American Physical Society has been authorized by the Council, acting in response to a petition signed by the forty Fellows and Members of the Society whose names are subjoined, and presented to the Council on May first.

"The field of this Division is defined to comprise all theories and all apparatus involving the forming, directing, shaping, and focussing of beams of electrons and ions. The Division is meant to include not merely those who are interested in electron microscopes, but also those who work with mass spectrographs, cyclotrons, any type of cathode-ray tube, and electron-diffraction apparatus. Nothing will preclude any member of this Division from joining also any subsequent Divisions. Meetings of the Division may be held (if the Council so authorizes) in conjunction with or separately from meetings of the Society.

"Any Fellow or Member of the American Physical Society may enroll in this Division. Those who enroll before August 15th, 1943, by sending a 'Form of Enrollment' to the Secretary of the Society, will be designated as 'original members' of the Division.

"The original Executive Committee of the Division will comprise a Chairman, a Vice-Chairman, a Secretary, and two additional members. Candidates for any or all of these five offices may be suggested by the original members, who should write the names on the Form of Enrollment. The Council has appointed a Committee of six (O. Beeck, F. G. Brickwedde, K. K. Darrow, A. J. Dempster, L. H. Germer, L. Marton) which will consider these suggestions and make nominations. Original members of the Division will then receive ballots, on which will be printed the names of these 'official' nominees, and also lines for the writing-in of substitute names. The Executive Committee thus elected will serve until the 1944 Annual Meeting of the Society, and its first obligation will be to draw up a set of By-Laws for the Division, these to go into effect only after approval by the members of the Division and by the Council of the Society.

"The Council takes this occasion to state that it will gladly receive and consider suggestions for the formation of further Divisions, each to be devoted to one or more special subjects within the realm of physics. Such modification of the structure and procedures of our Society seems timely, because of the recent great expansion of activity in physics, the increase in the number of physicists and in the diversity of their specialties, and the particular increase in the number of physicists in industry. The Council, however, is disinclined to favor a Division of Industrial Physics. It feels that the character and diversity of industrial physics are such as to be incompatible with the prescription for Divisions expressed in Article IX of the Constitution (quoted below); and also it wishes to promote unity between the physicists of industry and the physicists of the academic world, and feels that the formation of such a Division would work in the opposite sense.

"Article IX of the Constitution of the American Physical Society reads as follows:

1. The Council may, upon petition by members of the Society, form a Division within the Society charged with the advancement and diffusion of the knowledge of a specified subject or subjects in physics.
2. Each Division shall elect an Executive Committee, the Chairman of which shall report its activities and needs to the Council.
3. Any Division may be dissolved at the discretion of the Council."

KARL K. DARROW, *Secretary*
American Physical Society
Columbia University, New York 27, N. Y.

★

Navy's Need for Physicists

Activity of Axis submarines that menace our flow of men and materials to far-flung battle fronts has resulted in need for men qualified in the study of physics. The Navy is seeking competent instructors in physics, or men thoroughly familiar with the subject may qualify for commissions in the United States Naval Reserve. Although previous teaching experience is desirable it is not essential. Knowledge of college mathematics, preferably through calculus, is required of applicants. Selection of candidates will also be based upon qualities of leadership and good physical condition. Only applicants who are not in essential war industry or a federal agency will be considered for this program. Application for these vital and interesting billets can be made at the Office of Naval Procurement located in each major city.

★

Two New 50,000 Watt Stations Join United Nations Network in Radio War from Africa

From bases on the west coast of Africa, American-made radio has launched a new offensive against the Axis with two new stations spearheading the propaganda attack. The radio station of the Belgian Government is now on the air daily from Leopoldville, in Brazzaville, French Equatorial Africa; "The Voice of Free France," a 50,000 watt station is being completed. This will carry Fighting French news to France and all parts of French Colonial possessions from French Equatorial Africa. The new west African stations represent a new stage in the war of radio. They are ultra modern in every detail of their equipment. Tropical temperature and humidity, two of radio's natural enemies, are counter-attacked by a suitable choice of insulating and impregnation materials and air conditioning. Both Stations are equipped with RCA Radiophoto Service.

★

Textile Industry to Press Research

Plans for a five-year program of cooperative industrial research in the textile industry involving a $2,000,000 fund-raising project were announced recently by Fessenden S. Blanchard, president of the Textile Research

Institute, Inc., following approval by the group's directors at a meeting in the Hotel Roosevelt.

Declaring that there is an immediate need for intensive industrial research both for wartime needs and the peacetime situation ahead, the executive committee stated that the program contemplated attacking both problems on a cooperative industrial basis. The project will be undertaken with a recognized college or university.

The five-point program of the institute comprises fundamental research in all major fibers both natural and synthetic; applied and processing research in each of the major branches of the industry, economic research, a research information service, and scientific training of picked graduate students.

The institute was established in 1930 as the United States Institute for Textile Research.

★

New Course Offered in Ultra Short Waves

The Graduate Electrical Engineering Department of the Brooklyn Polytechnic Institute is offering as a part of the ESMWT program, a free advanced course in the Theory of Ultra Short Waves to train men for work in research laboratories of the war industries. This course which began July 1, and is to continue for 12 weeks, consists of one two-hour evening lecture per week by Mr. William MacLean, the prerequisites being: Differential Equations, Vector Analysis, and Electromagnetic Theory (Maxwell's Equations). Applications may be obtained from Miss M. W. Jones, Polytechnic Institute of Brooklyn, 85 Livingston Street, Brooklyn, New York.

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Mathematical Biophysics Table of Contents

The new September, 1943 issue of *The Bulletin of Mathematical Biophysics* has the following Table of Contents:

The Kinetics of Enzyme Inactivation. ALSTON S. HOUSEHOLDER AND GEORGE GOMORI.

Note on Anodal Excitation. ALSTON S. HOUSEHOLDER.

On the Theory of Amoeboid Movements. N. RASHEVSKY.

Studies in the Mathematical Biophysics of Discrimination and Conditioning: III. H. D. LANDAHL.

Book Review. D'Arcy Wenworth Thompson, on *Growth and Form.* GERHARDT VON BONIN.

★

New Members

Increased activity in research in the Rubber and Plastic Department of Foster D. Snell, Inc., has required the addition of three new members to its staff. The new members are Irving Merdinger, B.S., New York University, formerly with U. S. Rubber Company; Madlyn M. Sheldrick, B.S., Brooklyn College, and Asher Wollison, B.S., recent graduate of the College of the City of New York. Agatina Carbonaro, M.A., Columbia University, formerly with the Arabol Manufacturing Company, is now a member of the analytical staff of Foster D. Snell, Inc., also.

Necrology

Dr. Joseph S. Ames, fourth president of Johns Hopkins University, physicist and chairman of the National Advisory Committee for Aeronautics for twelve years, died June 24, 1943 at the age of 79 years. Dr. Ames was identified with the university from 1883 until 1935 when he retired becoming president emeritus. He was born in Manchester, Vermont, and graduated from Johns Hopkins in 1886. Dr. Ames was probably best known for his brilliant research in the field of aeronautics. For these services he received the Langley Gold Medal of the Smithsonian Institution in 1935.

New Books

The Theory of the Photographic Process

BY C. E. KENNETH MEES. Pp. 1124+x, Figs. 406, 15½×24 cm. The Macmillan Company, New York, 1942. Price $12.00.

This book presents a comprehensive survey of the science of the photographic process. Quite obviously most of the material is drawn from the many investigations conducted at the Kodak Research Laboratories, but similar work done elsewhere is by no means overlooked. The practice or art of photography does not come within its scope. Thus there is no discussion of cameras, lenses, and the taking of pictures. More surprising is the omission of both the science and art of color photography, although dye-coupler development is briefly discussed under development and toning. The material that is included is presented under six sections, namely: The Photographic Material, The Action of Light, Development and the After Processes, Sensitometry, Photographic Physics, and Optical Sensitizing. There are twenty-five chapters in all; the three chapters which make up the section on Photographic Physics are entitled: The theory of tone reproduction, The physics of the developed image, and The photographic aspects of sound recording.

This summary of photographic science is indispensable to the research worker in any branch of photography, giving a survey of the methods of investigation and the interpretation of results. The present status of the theory of the latent image and its production and development is ably discussed. It appears possible at last to present satisfactory explanations of the many peculiar properties of the photographic emulsion: the reciprocity failure, intermittency effect, solarization, Herschel effect, and many others.

The physical properties of the developed image and the methods for studying the same receive considerable attention. Principal properties are density, granularity and graininess, and reproduction of tone. As an important variation of the last, there is a chapter on the photographic aspects of sound recording.

On the whole, the book contains little that will directly help the average practicing photographer to make better pictures, though much of the information can be turned to

use by one who uses his head as part of his photographic equipment. The chapter of the theory of tone reproduction is particularly practical in its discussion of subjective and objective measures of print quality and their correlation. The treatment of the much-discussed subject of fine-grain development is surprisingly brief. It merely states the advantages of paraphenelenediamine and of halide solvents and warns against overlooking the effect of gamma on graininess in comparing various developers. On the other hand, the reactions and kinetics of development receive exhaustive treatment in a section of 300 pages.

As noted in the preface, the author received generous assistance from his colleagues at the Kodak Research Laboratories. This has ensured that the material in each section is practical, authoritative, and up to date, making this the most important book at present in the field of photographic science.

JOSEPH VALASEK
University of Minnesota

Innovations in Instruments

New Precision Instrument for Measuring Gloss

The new Aminco-Scott Glossmeter (goniophotometer) measures high, medium, and low gloss (from zero to 100 percent) or plane surfaces of materials over $2\frac{1}{8}\times 3$ inches in size such as paint finishes, enamels, lacquers, metals, wood, paper, plastics, glass, etc. Results are in terms of the I.C.I. normal observer and I.C.I. Illuminant *C*.

The kinds of gloss (relative apparent reflectance) measured with this instrument are specular gloss, contrast gloss, distinctness-of-image gloss, absence-of-bloom gloss, and many other optical properties of surfaces of all kinds. It is especially useful for A.S.T.M. method D523 for measuring specular gloss of paint finishes. Some suggested supplementary uses are the measurement of the hiding power of deposited finishes, cleansing power of soaps, relative apparent reflectance of plane surfaces for obtaining Munsell value, index of refraction, resistance of surfaces to abrasion, weathering, wear, etc. Illumination is adjustable from minus 30 degrees to plus 70 degrees from the normal. The receptor is adjustable from plus 30 degrees to minus 70 degrees from the normal. Angles may be read to 1 minute of arc. Measurements of relative apparent reflectance from zero to 100 percent (in steps of 0.01 percent) can be made. Measurements can be made rapidly, and the instrument has sensitivity and wide range and may be used without neutral filters, wedges, or similar devices. The instrument need not be operated in a darkened room and can be used on 110–120 volts, 60 cycles (controlled frequency), single phase a.c., and is unaffected by fluctuations in line voltage. The entire outfit consisting of (1) goniophotometer, (2) reference plate and sample holder, (3) control and measuring unit, (4) galvanometer, and glass reference plate, weighs approximately 55 lb. Bulletin DD2115 gives complete description and specimen curves and may be obtained from the American Instrument Company, Silver Spring, Maryland.

New Vibration Fatigue Testing Machine

The All American Tool and Manufacturing Company, 1014 Fullerton Parkway, Chicago, has announced in a booklet entitled *All American Vibration Fatigue Testing Equipment*, Catalog *F*, the addition of the Model 100 to its line of vibration fatigue testing machines. The new unit handles parts or assemblies up to 100 pounds, which are to undergo vibration fatigue tests. Table area $15''\times 18''$ has 115 tapped holes for bolting on objects, and movement is horizontal. The frequency is adjustable while machine is running from 10–60 cycles per second and is recorded on an electric tachometer. Displacement, from 0 to 0.125 inch (adjustable), covers the full range encountered by parts subjected to vibration in actual service. The maximum capacity is 23g, unit base area $24''\times 42''$. Weight 550 lb. $1\frac{1}{2}$-hp motor supplies power. Eyebolts in the base permit handling with shop hoists or cranes. This model is designed for use in laboratories or inspection departments to test fabricated airframe and aircraft engine parts, navigation instruments, radio and electronic equipment, molded plastic parts, and a variety of other parts, materials, and chemicals to determine the effects of vibration. Catalog *F* sent on request.

New Electronic Development Reduces Critical Drain on Strategic Mica Stockpile

"Polectron" products, new thermo plastic resins with unusual high softening temperatures, low dielectric loss, and excellent water resistance, have been announced by the General Aniline and Film Corporation. Their properties make them useful in dielectrical materials for replacement of mica in radio condensers and also suggest many other electronic and electrical applications. Impregnation of electrical coils, windings, and capacitors where high insulation values must be maintained at elevated temperatures, and water and moisture seals for various types of electrical equipment, are among the indicated uses. "Polectron" products are now available in limited quantities. The General Aniline and Film Corporation is installing facilities to provide ample supply for industrial applications and will gladly cooperate with manufacturers in most effectively adapting Polectron products for their needs.

Rheostat and Charts

The Ohmite Manufacturing Company is introducing two new innovations in the form of: (1) the Ohmite Circular Slide-Wire Rheostat designed especially for low resistance low wattage applications. This Ohmite rheostat-potentiometer has found several applications in the instrument field. The provision of three terminals allows the unit to be used as a potentiometer or voltage divider. Shafts for knob control or for screw driver control can be supplied. These units are made to order to suit the particular application and inquiries on this basis are welcomed. (2) A $26''\times 36''$ Ohm's Law and Parallel Resistor charts for wall hanging, to aid teachers, students, technicians, and engineers in war training and in industry. The Ohm's Law chart is used for graphical determination of

wattage, voltage, current, and resistance. The Parallel Resistor chart is used for graphical determination of the resistance of resistors in parallel. The two wall charts are available without charge to schools, training centers, engineers, procurement officers, and plant executives who write for it on official stationary or company letterhead to the Ohmite Manufacturing Company, 4835 Flournoy Street, Chicago 44, Illinois.

Radionic Frequency Meter

New radionic frequency meters are now in production in four new models by the Fred E. Garner Company, 43 East Ohio Street, Chicago, Illinois. All models are crystal-controlled and, by means of a class "C" harmonic amplifier circuit embodied in the units, accurate frequency carrier signals are provided every 10 kc and every 100 kc from one hundred cycles to forty-five megacycles. A carrier signal is also produced every 1000 kc from one megacycle to one hundred twenty megacycles. A convenient panel-mounted "on-off" switch permits use of a 1000-cycle modulated note.

Special models designed for use under adverse conditions are available equipped with two precision crystals that have been ground to produce exact frequencies of 100 and 1000 kc and tested for efficient operation at temperatures from −35° to 55° centigrade and have temperature coefficients of maximum drift of only 2 and 3 cycles per megacycle per degree centigrade, respectively. Models are available for either a.c. or portable battery operation.

New Instrument Booklets

Acmé Industrial Company of Chicago has recently prepared a highly instructive booklet on light wave measurements. Printed in two colors and composed of twelve pages, the new booklet contains various descriptive charts, illustrations, diagrams, and detailed instructions simplifying the understanding of light wave measurement. It explains the practical everyday use of light waves in shop measurements based on Acme's experience in their own shop, and claims that any mechanic can measure in millionths of an inch by following the instructions outlined in the new booklet. Copies mailed upon request from Acme Industrial Company Department A.P., 200 N. Laflin Street, Chicago, Illinois.

Allied Radio Data Handbook, edited by Lieutenant Nelson M. Cooke, United States Navy, U. S. Naval Research Laboratory, Washington, D. C., is published by, and may be purchased directly from Allied Radio Corporation, 833 West Jackson Boulevard, Chicago, Illinois. Forty-eight pages, six by nine inches; price 25¢ postpaid. This is a comprehensive, condensed handbook of formulas, charts, and data most commonly used in the field of radio and electronics. It is divided into four parts: Mathematical Data, Radio and Electronic Formulas, Engineering and Servicing Information, and a complete set of four-place Log and Trig Tables, with all subjects cross-indexed for ready reference. An aid to students who want fundamentals, the serviceman, the experimenter, or the engineer.

Synthetic Rubber, 1943, a publication of U. S. Rubber Company, describes the five commercial types of synthetic rubber. It traces the development of synthetic rubber from its laboratory beginnings, describes the properties of commercial synthetic rubbers, and relates briefly the part played by the U. S. Rubber Company in this field. The publication includes photographs of synthetic rubber manufacture, many diagrams, and a chart compiled from the experience of plants and laboratories of the company, giving the relative physical and chemical properties of natural rubber and of the five types of synthetic rubber. This booklet has had a limited distribution to government agencies and allied industry, but is now available upon application to the U. S. Rubber Company, Synthetic Rubber Division, 1230 Sixth Avenue, New York, New York (40 pages).

Contributed Original Research

The Vibration Characteristics of "Free-Free" Circularly Curved Bars

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AND
F. P. BUNDY,† *Harvard University, Cambridge, Massachusetts and The Cooper-Bessemer Corporation, Mt. Vernon, Ohio*

(Received June 3, 1943)

The positions of the nodal points and the values of the frequencies of vibration have been determined for the first five or six modes of parallel and transverse vibration of circularly curved bars of uniform cross section with central angles ranging from 356° to 60°. For vibration in the plane of curvature (parallel) the relative positions of the nodal points are the same for the same central angles, regardless of the type of cross section. Also, for the parallel vibration the frequency in the nth mode is given by the expression,

$$f_n=\frac{\theta^2K(n,\theta)}{L^2}\left(\frac{B}{m}\right)^{\frac{1}{2}},$$

where θ is the half central angle in radians, L is the length, B is the bending stiffness of the cross section about an axis perpendicular to the plane of the ring, m is the mass per unit length, and K is a "frequency constant" which depends upon n and θ. For $n>1$ or 2, K may be expressed accurately as,

$$K(n,\theta)=S^2(\theta)[n-g(\theta)]^2K(1,\theta).$$

Graphs of $S(\theta)$, $g(\theta)$, and $K(1,\theta)$ are presented. For vibrations transverse to the plane of curvature the relative positions of the nodal points depend only upon the central angle. The frequency in the nth mode of transverse vibration is given by the expression,

$$f_n=\frac{\theta^2\psi(n,\theta,A/C)}{L^2}\left(\frac{A}{m}\right)^{\frac{1}{2}},$$

where θ, L, and m are the same as defined above, A is the bending stiffness of the cross section about an axis in the radial direction, and ψ is a "frequency constant" which depends upon n, θ, and the A/C ratio. For $n>2$, ψ may be expressed quite accurately as,

$$\psi(n,\theta,A/C)=Q^2(\theta,A/C)[n-q(\theta,A/C)]^2\psi(1,\theta,A/C).$$

Graphs of $Q(\theta,A/C)$, $q(\theta,A/C)$, and $\psi(1,\theta,A/C)$ are presented.

INTRODUCTION

THE vibration characteristics of nearly-complete circular rings were investigated and reported by Bundy and Bankes in 1942.[1] This work has been extended to the "free-free" vibration of circularly curved bars of uniform cross section with central angles ranging from 356° to 60°. The experimental investigation reported in this paper was limited to the determination of the positions of the nodal points and the frequencies of vibration. No measurements were taken of the distribution of amplitude of motion around the bars.

The theoretical determination of the frequency constants for the first mode of vibration in the plane of circularly curved bars has been made by Ikebe,[2] using a modified Rayleigh-Ritz method. The agreement between Ikebe's calculated values and the experimentally observed ones is quite close.

The conventions and notations used in this paper will be as follows: The coordinate system has its origin on the "neutral line" which is the locus of the center of gravity of the cross-sectional area. The x axis is taken radially inward, the y axis perpendicular to the plane of the ring, and the z axis tangent to the "neutral-line."

Also, I_x = moment of inertia of the cross section about the x axis,
I_y = moment of inertia of the cross section about the y axis,
E = Young's modulus,
$A=EI_x$ = bending stiffness about the x axis,
$B=EI_y$ = bending stiffness about the y axis,
C = torsional stiffness about the z axis,
m = mass per unit length along the "neutral-line,"
R = radius of curvature of the neutral line,

* Now in the U. S. Army Air Corps.
† On leave of absence from Ohio University.
[1] F. P. Bundy and C. W. Bankes, J. App. Phys. **13**, 652 (1942).
[2] T. Ikebe, Inst. of Phys. and Chem. Research, Tokyo, Sci. Paper No. 796, pp. 680–712 (July, 1938).

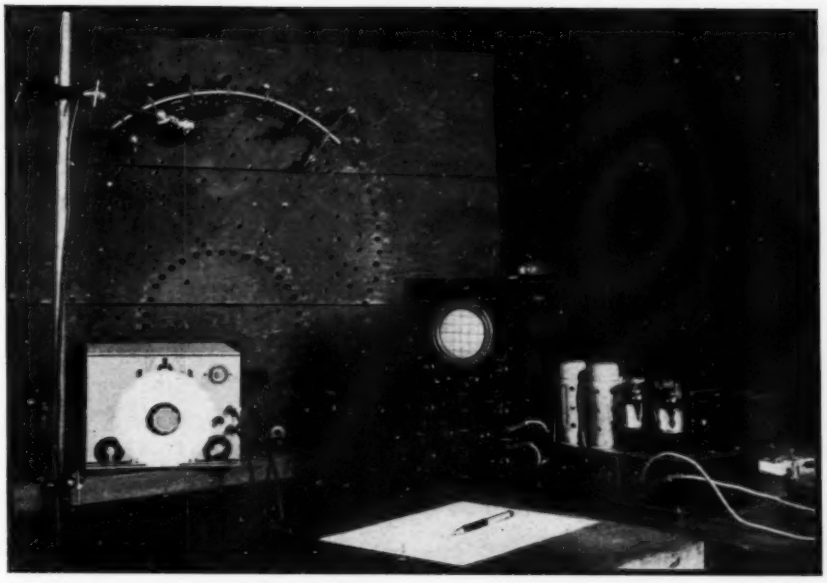

FIG. 1. Photograph of experimental set-up.

D = diameter corresponding to the radius of curvature,
L = length of neutral line,
θ = half central angle subtended by the curved bar,
n = mode of vibration.

Vibrations in the plane of the ring are designated as "parallel," and those perpendicular to the plane of the ring as "transverse."

EXPERIMENTAL METHOD

Six rings were made from cold-rolled steel bars by rolling them in a bending roll and afterwards grinding them to accurate cross section. The original bars were selected with cross sections which caused the resulting rings to have A/C ratios which lay between 0.8 and 21. The diameters of the rings ranged from 49 cm to 57 cm. The elastic constants of the steel bars were measured before and after being rolled into rings, using the methods described by Bundy and Bankes.[1] Table I lists the physical constants of the six rings used in this investigation.

Measurements of nodal points and frequencies were made for all six rings when their central angles, 2θ, were 356°. Then the ends of the bars were cut off to give central angles of 300° and a new set of measurements taken. The bars were cut off successively to 240°, 180°, 120°, 90°, and 60°, measurements being made in each case.

The rings were supported at the nodal points by flexible rubber bands which were attached to wooden pegs placed in convenient holes in a large wooden panel (see Fig. 1). The vibration was excited by striking the bar at an antinodal point while holding it lightly with the fingers at one or more of the nodal points. After striking the bar the fingers were removed from the nodal points and the bar literally vibrated "freely." This method of excitation was used because of its utter simplicity and because earlier experiments had shown that magnetic methods of excitation influenced the frequency of vibration considerably.

TABLE I. Physical constants of the rings used.

Ring	D (cm)	b_y (cm)	c_z (cm)	β	m (g/cm)
I	51.9	0.433	1.259	0.261	4.256
II	49.7	0.632 = diam. of cross section			2.45
III	59.6	0.954	0.630	0.197	4.69
IV	55.9	1.208	0.475	0.250	4.45
V	54.8	1.166	0.311	0.277	2.86
VI	56.5	1.729	0.321	0.295	4.35

Ring	A (dyne-cm²)	B (dyne-cm²)	C (dyne-cm²)	A/C
I	17.3×10^{9}	14.6×10^{10}	21.3×10^{9}	0.812
II	16.1×10^{9}	16.1×10^{9}	12.6×10^{9}	1.28
III	92.4×10^{9}	40.4×10^{9}	37.8×10^{9}	2.44
IV	14.2×10^{10}	21.9×10^{9}	25.9×10^{9}	5.48
V	83.4×10^{9}	59.3×10^{8}	77.7×10^{8}	10.7
VI	28.0×10^{10}	96.6×10^{8}	13.5×10^{9}	20.7

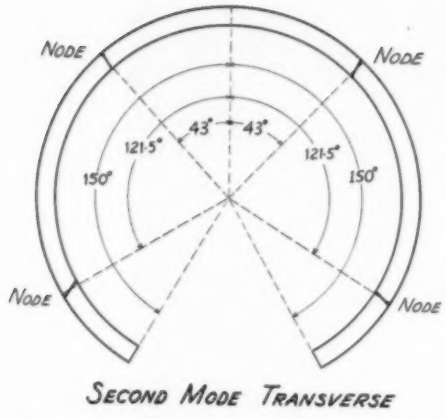

FIG. 2. Nodal lines for a transverse vibration.

The positions of the nodal points were determined quite accurately by rubbing a light "feeler-wire" along the bar as it vibrated. For the parallel vibrations there are no true nodal points because the motion consists of radial and tangential components and both of these components never vanish at the same point on the ring. The nodal points listed for the parallel vibration are those points for which the radial component of the motion vanishes.

For the transverse vibration of the rings which were thick in the x direction and thin in the y direction it was found that the nodal lines were not parallel to the radius at that position but were about as shown in Fig. 2, which shows the case of the second mode transverse for the 300° Ring *I*. The nodal points listed for transverse vibration correspond to the points where the nodal lines cross the neutral axis.

The frequencies of vibration lower than about 150 c.p.s. were measured with an accuracy of 0.5 percent or better by stroboscopic comparison of the vibrating ring with a calibrated variable-length piano-wire reed as described in the report by Bundy and Bankes.[1] The frequencies of vibration which were above the accurate range of the piano-wire reed method were measured by placing a crystal microphone near an antinodal point of the vibrating bar and comparing its preamplified output with that of a Carron audio beat-frequency oscillator on a cathode-ray oscillograph. The Carron oscillator was previously calibrated against the Bureau of Standards broadcast of standard 440 c.p.s. and three standard tuning forks having frequencies of 320, 384, and 512 c.p.s. It was found consistently possible to set the oscillator within 0.2 percent of the standard frequencies and consequently the measurements made with it are believed to have the same accuracy.

RESULTS

The positions of the nodal points for any given mode and type of vibration were found to be the same for all the rings of a given central angle, independent of the type of cross section, providing the cross section is uniform along the entire length. Table II lists the positions of the nodal points, in terms of fractional length of the bars, for the parallel vibrations for bars subtending central angles from 356° to 0° (0° corresponds to a straight bar). Table III lists the corresponding data for the transverse vibration. Figures 3 and 4 show graphically how the positions of the nodal points shift gradually to those of a straight bar as the central angle is decreased. It is also clear that the positions of the nodal

TABLE II. Positions of the nodal points of the parallel vibrations in terms of the fractional lengths of the bar.

	n	Positions of the nodal points							
356°	1			0.416		0.584			
	2			0.205	0.500	0.795			
	3		0.121	0.360		0.640	0.879		
	4		0.087	0.280	0.500	0.720	0.913		
	5	0.070	0.229	0.411		0.589	0.771	0.930	
	6	0.053	0.191	0.343	0.500	0.657	0.809	0.947	
300°	1			0.365		0.635			
	2			0.185	0.500	0.815			
	3		0.113	0.359		0.641	0.887		
	4		0.085	0.280	0.500	0.720	0.915		
	5	0.069	0.228	0.410		0.590	0.772	0.931	
240°	1			0.321		0.679			
	2			0.167	0.500	0.833			
	3		0.107	0.358		0.642	0.893		
	4		0.081	0.279	0.500	0.721	0.919		
180°	1			0.289		0.711			
	2			0.153	0.500	0.847			
	3		0.103	0.357		0.643	0.897		
120°	1			0.262		0.738			
	2			0.145	0.500	0.855			
	3		0.099	0.355		0.645	0.901		
90°	1			0.245		0.755			
0°	1			0.224		0.776			
	2			0.132	0.500	0.868			
	3		0.094	0.356		0.644	0.906		
	4		0.076	0.277	0.500	0.723	0.924		
	5	0.060	0.223	0.407		0.593	0.777	0.940	
	6	0.047	0.191	0.346	0.500	0.654	0.809	0.953	

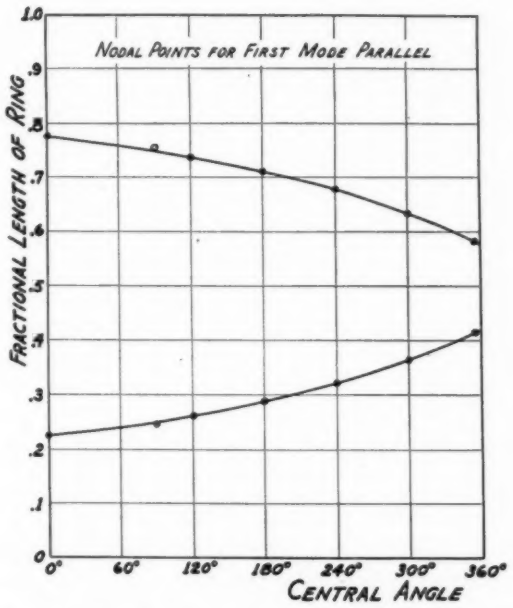

FIG. 3. Shift of position of nodal points of first mode parallel *vs.* central angle.

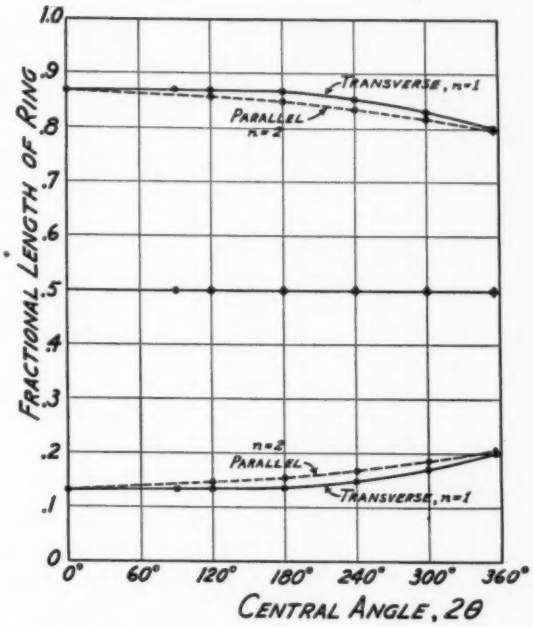

FIG. 4. Shift of positions of nodal points of first mode transverse and second mode parallel *vs.* central angle.

points for corresponding modes (i.e., same number of nodes and antinodes) of parallel and transverse vibration are slightly different, and the difference diminishes as the mode number increases. The greatest shift is observed for the nodal points near the free ends of the bars.

It was found that for the parallel vibrations the frequency of vibration could be expressed,

$$f_n = \frac{K(n,\theta)}{D^2}\left(\frac{B}{m}\right)^{\frac{1}{2}}, \qquad (1)$$

where K is independent of the type of cross section and depends only upon the mode of vibration n and the central angle 2θ. The other terms have the meanings given them in the Introduction. It was also found that when the square roots of the frequency ratios of rings of a given central angle were plotted against the mode number a straight line could be drawn through the points for $n>1$ or 2. The slopes and intercepts of these lines vary for the rings of different central angles. This effect is illustrated in Fig. 5.

TABLE III. Positions of the nodal points of the transverse vibrations in terms of the fractional lengths of the bar.

	n	Positions of the nodal points						
356°	1			0.200	0.500	0.800		
	2		0.101	0.360		0.640	0.899	
	3		0.071	0.269	0.500	0.731	0.929	
	4	0.052	0.213	0.408		0.592	0.787	0.948
	5	0.046	0.183	0.342	0.500	0.658	0.817	0.954
300°	1			0.170	0.500	0.830		
	2		0.095	0.357		0.643	0.905	
	3		0.075	0.272	0.500	0.728	0.925	
	4	0.058	0.220	0.407		0.593	0.780	0.942
	5	0.048	0.188	0.343	0.500	0.657	0.812	0.952
240°	1			0.148	0.500	0.852		
	2		0.094	0.354		0.646	0.906	
	3		0.075	0.273	.500	0.727	0.925	
180°	1			0.134	0.500	0.866		
	2		0.089	0.352		0.648	0.911	
120°	1			0.133	0.500	0.867		
	2		0.091	0.352		0.646	0.909	
90°	1			0.132	0.500	0.868		
0°	1			0.224		0.776		
	2			0.132	0.500	0.868		
	3		0.094	0.356		0.644	0.906	
	4		0.076	0.277	0.500	0.723	0.924	
	5	0.060	0.223	0.407		0.593	0.777	0.940
	6	0.047	0.191	0.346	0.500	0.654	0.809	0.953

TABLE IV. Values of $K_1\theta^2$, $S(\theta)$, and $g(\theta)$ *vs.* 2θ for parallel vibration.

2θ	$K_1\theta^2$	$S(\theta)$	$g(\theta)$
356°	2.751	0.797	0.21
300°	2.700	0.791	0.02
240°	2.750	0.779	−0.13
180°	2.887	0.752	−0.25
120°	3.148	0.715	−0.38
90°	3.300	0.693	−0.44
60°	4.432	0.679	−0.47
0°	3.618	0.667	−0.50

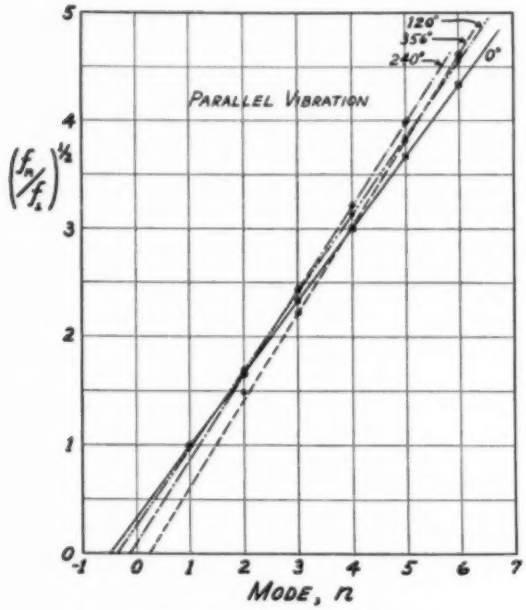

FIG. 5. $(f_n/f_1)^{\frac{1}{2}}$ *vs.* n for parallel vibration.

The values of the slopes $S(\theta)$ and the intercepts $g(\theta)$ are given in Table IV and are plotted against the central angle 2θ in Fig. 6.

This behavior of the frequency ratios immediately suggested that Eq. (1) could be written in the form,

$$f_n=\frac{S^2(\theta)[n-g(\theta)]^2K(1,\theta)}{D^2}\left(\frac{B}{m}\right)^{\frac{1}{2}}, \quad \text{for } n\geq 2. \quad (2)$$

Thus, from the experimental values of $K(1,\theta)$ it is possible to calculate quite accurately the frequency of any of the higher modes of vibration.

Perhaps a more convenient way of expressing Eq. (2) is the following,

$$f_n=\frac{S^2(\theta)[n-g(\theta)]^2\theta^2K(1,\theta)}{L^2}\left(\frac{B}{m}\right)^{\frac{1}{2}}, \quad (3)$$

where L is the length of the bar. The values of $\theta^2K(1,\theta)$ as determined experimentally in this investigation are given in Table IV and are compared with the theoretical values of Ikebe[2] in Fig. 7. The agreement is excellent for central angles up to 180°. For central angles greater than 180° the greatest discrepancy is only about 1 percent.

For the transverse vibration the frequency may be expressed as

$$f_n=\frac{\psi(n,\theta,A/C)}{D^2}\left(\frac{A}{m}\right)^{\frac{1}{2}}. \quad (4)$$

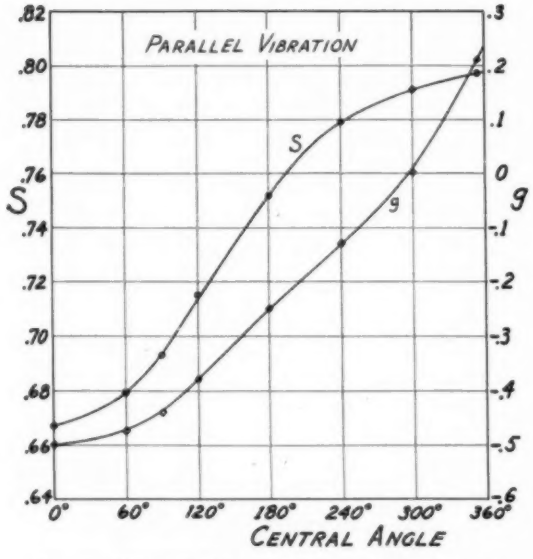

FIG. 6. $S(\theta)$ and $g(\theta)$ *vs.* 2θ for parallel vibration.

In this case the "frequency-constant" ψ depends not only upon the mode number and central angle, but also upon the ratio of the bending stiffness to the torsional stiffness, as both bending and twisting strains are developed in the transverse vibration. Just as in the case of the parallel vibration, it was found that when the square roots of the frequency ratios $(f_n/f_1)^{\frac{1}{2}}$ for a given

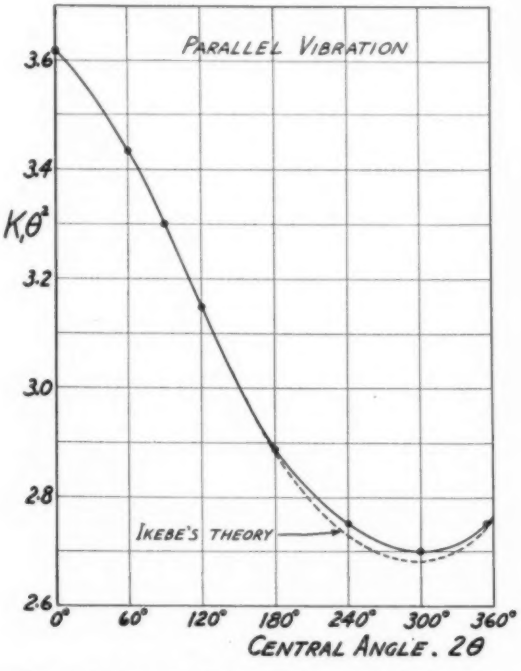

FIG. 7. Values of $K_1\theta^2$ *vs.* 2θ for parallel vibration.

curved bar were plotted against the mode numbers, the points lay along a straight line except for the first, or first and second points. The slopes and intercepts of these straight lines vary with the central angle and the A/C ratio of the curved bar.

The general equation of these families of straight lines may be written as

$$(f_n/f_1)^2 = Q(\theta, A/C)[n - q(\theta, A/C)]. \quad (5)$$

It follows then that Eq. (4) above may be put in the form

$$f_n = \frac{Q^2(\theta, A/C)[n - q(\theta, A/C)]^2 \psi(1, \theta, A/C)}{D^2} \left(\frac{A}{m}\right)^{\frac{1}{2}}, \quad (6)$$

or

$$f_n = \frac{Q^2(\theta, A/C)[n - q(\theta, A/C)]^2 \theta^2 \psi(1, \theta, A/C)}{L^2} \left(\frac{A}{m}\right)^{\frac{1}{2}}. \quad (7)$$

The experimental values of $Q(\theta, A/C)$ and $q(\theta, A/C)$ are listed in Table V. The values of $Q(\theta, A/C)$ are presented graphically two ways in Figs. 8 and 9. The values of $q(\theta, A/C)$ are shown in two different ways in Figs. 10 and 11. For finding the values of Q and q for any given bar Figs. 9 and 11 are more useful than Figs. 8 and 10 because in general it is easier to interpolate between the lines of constant central angle than it is to interpolate between the lines of constant A/C. The experimental values of $\theta^2\psi(1, \theta, A/C)$ are listed in Table VI. Figures 12 and 13 are graphs of $\theta^2\psi(1, \theta, A/C)$ against the central angle 2θ (with lines of constant A/C) and against

TABLE V. Values of $Q(\theta, A/C)$ and $q(\theta, A/C)$.

2θ	A/C	$Q(A/C)$	$q(A/C)$
356°	0.812	0.708	−0.36
357°	1.28	0.760	−0.29
357°	2.44	0.885	−0.01
355°	5.48	1.03	0.24
354°	10.7	1.19	0.52
355°	20.7	1.26	0.61
300°	0.812	0.628	−0.60
	1.28	0.676	−0.48
	2.44	0.783	−0.25
	5.48	0.918	0.01
	10.7	1.05	0.32
	20.7	1.12	0.37
240°	0.812	0.559	−0.79
	1.28	0.590	−0.70
	2.44	0.673	−0.49
	5.48	0.777	−0.28
	10.7	0.896	−0.02
	20.7	0.954	0.05
180°	0.812	0.499	−0.98
	1.28	0.520	−0.92
	2.44	0.575	−0.74
	10.7	0.740	−0.38
120°	0.812	0.445	−1.20
	1.28	0.453	−1.16
	2.44	0.476	−1.07
	5.48	0.520	−0.95
	10.7	0.586	−0.77
	20.7	0.593	−0.74
90°	0.812	0.428	−1.30
	1.28	0.430	−1.28
	2.44	0.461	−1.16
	5.48	0.464	−1.10

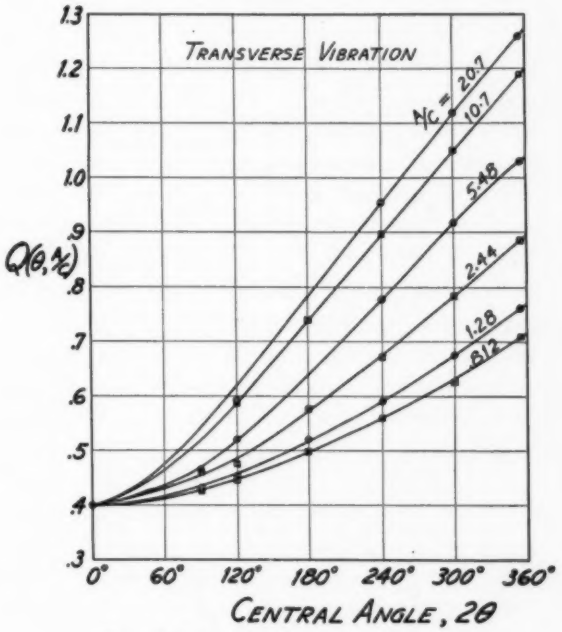

FIG. 8. $Q(\theta, A/C)$ plotted as Q *vs.* 2θ, lines of constant A/C.

TABLE VI. Experimental values of $\theta^2\psi(1, \theta, A/C)$.

2θ	Ring I A/C =0.812	Ring II A/C =1.28	Ring III A/C =2.44	Ring IV A/C =5.48	Ring V A/C =10.7	Ring VI A/C =20.7
356°	3.92	3.33	2.57	1.80	1.34	0.94
300°	4.72	4.13	3.21	2.28	1.69	1.23
240°	5.87	5.23	4.24	3.05	2.30	1.66
180°	7.11	6.53	5.60	4.17	3.23	2.35
120°	8.43	8.06	7.24	5.81	4.75	3.52
90°	9.09	8.78	8.20	6.92	5.64	4.32
60°	9.53	9.29	8.95	7.97	6.80	
0°	10.05	10.05	10.05	10.05	10.05	10.05

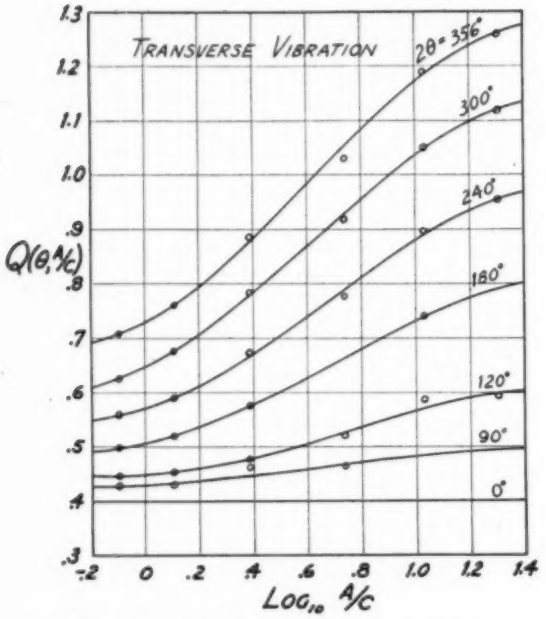

FIG. 9. $Q(\theta, A/C)$ plotted as Q *vs.* $\log_{10} A/C$, lines of constant 2θ.

$\log_{10} A/C$ (with lines of constant 2θ), respectively.

As an illustration of how the tables and graphs given above can be used in calculating the vibration frequencies of a given circularly curved bar, consider a steel bar with an x dimension of 0.5 cm, y dimension of 1.0 cm, $L=40$ cm, $2\theta=150°$ $=2.62$ radians, $E=20.2\times10^{11}$ dynes/cm², and let it be required to calculate the frequencies of the seventh mode parallel and fifth mode transverse. From the data given, $A=8.42\times10^{10}$ dyne cm², $B=2.10\times10^{10}$ dyne cm², $C=2.29\times10^{10}$ dyne cm²,

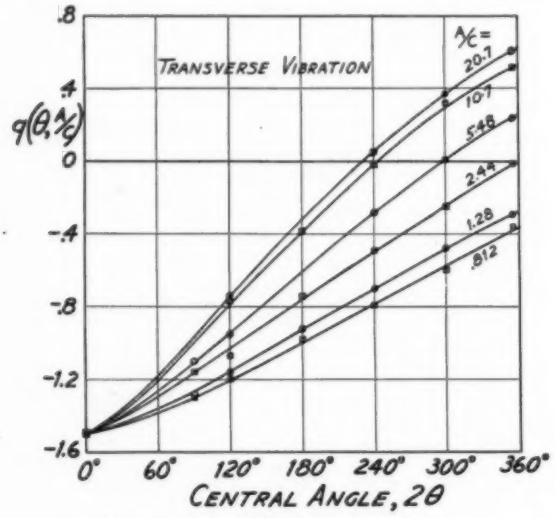

FIG. 10. $q(\theta, A/C)$ plotted as q *vs.* 2θ, lines of constant A/C.

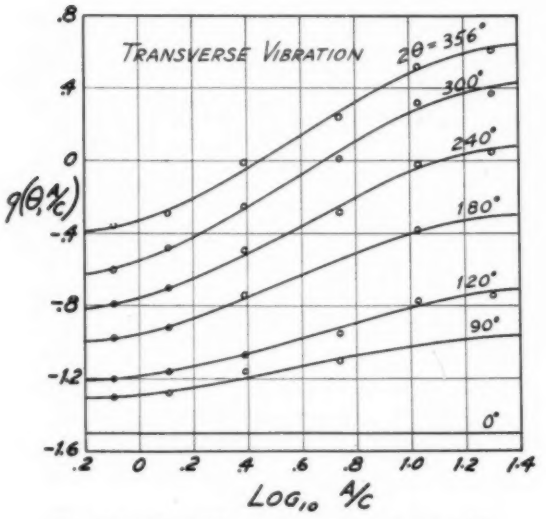

FIG. 11. $q(\theta, A/C)$ plotted as q *vs.* $\log_{10} A/C$, lines of constant 2θ.

$A/C=3.67$, and $m=3.9$ grams/cm. From Fig. 7, $\theta^2K(1, \theta)$ for 150° is 3.00. From Fig. 6, $S(\theta)$ and $g(\theta)$ for $2\theta=150°$ are 0.733 and -0.315, respectively. Hence, using Eq. (3),

$$f_7(\text{parallel}) = \frac{(0.733)^2[7+0.315]^2(3.00)}{(40)^2}\left(\frac{2.10\times10^{10}}{3.90}\right)^{\frac{1}{2}}$$

$$=3950 \text{ c.p.s.}$$

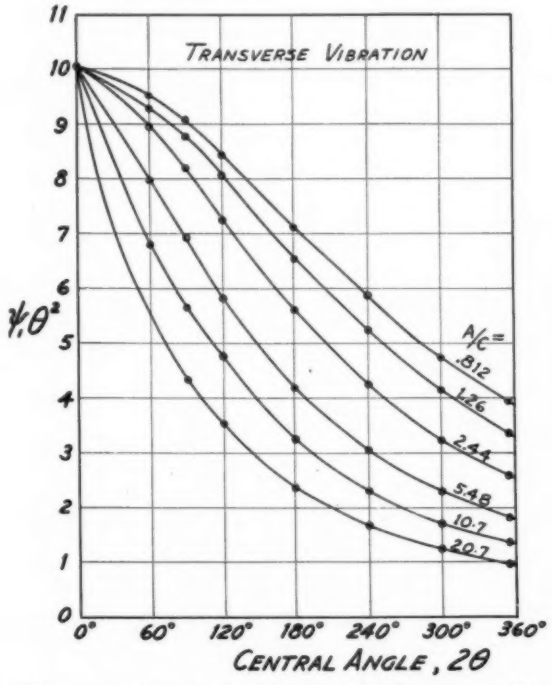

FIG. 12. $\theta^2\psi(1, \theta, A/C)$ *vs.* 2θ (lines of constant A/C).

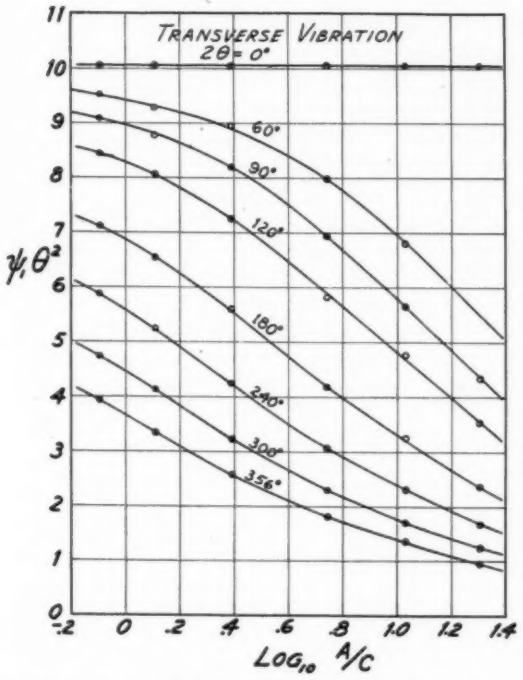

FIG. 13. $\theta^2\psi(1, \theta, A/C)$ *vs.* $\log_{10} A/C$ (lines of constant 2θ).

From Fig. 12 or 13 the value of $\theta^2\psi(1, \theta, A/C)$ for $2\theta = 150°$ and $A/C = 3.67$ is 5.73. From Fig. 8 or 9, $Q(\theta, A/C) = 0.56$, and from Fig. 10 or 11, $q(\theta, A/C) = -0.83$. Hence, using Eq. (7),

$$f_5(\text{transverse}) = \frac{(0.56)^2[5+0.83]^2(5.73)}{(40)^2}\left(\frac{8.42\times10^{10}}{3.90}\right)^{\frac{1}{2}}$$

$$= 5630 \text{ c.p.s.}$$

CONCLUSIONS

The theoretical frequency constants, $\theta^2K(1, \theta)$ derived by Ikebe are found to agree very closely with the experimentally observed values. About one percent discrepancy exists in the values for central angles greater than 180°.

On the basis of the expressions derived empirically from data gathered in the present investigation it is possible to calculate with reasonable accuracy the frequency of vibration, parallel or transverse, of any incomplete, free-free, circularly curved bar of uniform cross section if its mechanical constants are known.

The greatest errors in the determination of accurate values in this investigation are due to the lack of homogeneity of structure of the metal in the rings. Considerable difficulty was experienced in getting measurements of the elastic constants which were self consistent within one percent.

This present investigation suggests several related investigations which have yet to be done. Some of these are the measurements of the distribution of amplitudes of vibration along circularly curved bars of the type studied in this present paper, the investigation of the torsional modes of vibration in circularly curved free-free bars, the development of the theory of the transverse vibration of free-free circularly curved bars, the vibration characteristics of clamped-clamped, clamped-hinged, hinged-hinged, clamped-free, and hinged-free circularly curved bars of uniform cross section. Some special cases of circularly curved bars with non-uniform cross section would also be of interest for investigation.

The authors wish to express their gratitude to Mr. Gehres and Mr. Boyer of the Cooper-Bessemer Corporation for their interest and encouragement in the present investigation and for their generosity in providing the accurately-machined ring specimens.

Calendar of Meetings

September

6–10 American Chemical Society, Pittsburgh, Pennsylvania
12–13 American Mathematical Society, New Brunswick, New Jersey
21–24 Technical Association of Pulp and Paper Industry, Chicago, Illinois

October

7–9 Optical Society of America, Pittsburgh, Pennsylvania
13–16 Electrochemical Society, Inc., New York, New York
18–23 American Welding Society, Chicago, Illinois
23 Metropolitan Section of the American Physical Society, New York, New York
29–30 Society of Rheology, New York, New York

November

14–16 American Institute of Chemical Engineers, Pittsburgh, Pennsylvania
26–27 American Physical Society, Chicago, Illinois
26–27 Central Association of Science and Mathematics Teachers, Chicago, Illinois

December

27–Jan. 1 American Association for the Advancement of Science, Cleveland, Ohio

A Spectrophotometric Method for the Analysis of Multicomponent Mixtures and Its Infra-Red Application

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(Received April 8, 1943)

A general method has been developed for spectrophotometric analysis of multicomponent mixtures. The method is based on the assumption that the optical density of a mixture equals the sum of the optical densities of the components, although the transmissions of the individual components may not follow Beer's law. The application of the method to infra-red absorption of vapor samples is described in detail. The results of tests using a six-component C_4 hydrocarbon mixture are given. The method is especially useful for the rapid routine analysis of large numbers of samples containing the same components, and therefore is well suited for plant control purposes.

INTRODUCTION

THE value of infra-red spectrophotometry as an analytical tool in chemical industry has been emphasized in several recent articles.[1–5] The quantitative analytical procedures described have been applied to two-component samples, although extensions to multicomponent mixtures have been suggested. A method for analyzing multicomponent mixtures by measuring their infra-red absorption has been developed and tested at this laboratory using mixtures containing *n*-butane, isobutane, 1-butene, cis-2-butene, trans-2-butene, and isobutene. However, notwithstanding the usefulness of this particular analysis in the petroleum industry, the above mixture should be regarded as only one application of the method to be described below. Indeed, nothing in the method limits its use to the infra-red region of the spectrum or to hydrocarbon mixtures.

Spectrophotometric analysis for all the components, or for one component, of a mixture is simple in those rare cases where sufficient spectral positions, at which only one component absorbs, can be found. Although more calculation is involved, the analysis of mixtures not fulfilling the above condition is equally straightforward if the absorptions measured obey Beer's law. These conditions are seldom fulfilled closely enough to give sufficient accuracy when analyzing routine samples for control in chemical manufacturing. In the two-component analyses referred to above these difficulties were overcome by using a strictly empirical calibration based on synthetic samples. However, the number of samples required to represent adequately the possible compositions of a six-component mixture would be too great. This in addition to the difficulty of representing graphically the information gained by measuring the absorption of such a mass of samples, precludes the use of a strictly empirical basis for the analysis of multicomponent mixtures.

The semi-theoretical method to be described below is based on measurements of the transmissions of the pure components. Consequently, the transmission data must be accurate—i.e., they must be characteristic of the components and must not be influenced by false energy, gas law deviations, non-reproducibility of the spectrophotometer, or non-linearity of the thermopile or galvanometer. A general knowledge of the spectra of the components is needed in order to select the spectral positions at which transmission measurements are to be made. These are chosen so that the principal contribution to the absorption at each position is due to a different component of the mixture. This means that each analytical problem to which the method is applied must be treated as an individual case.

GENERAL METHOD

For monochromatic radiation the optical density* of a mixture equals the sum of the optical

[1] N. Wright, Ind. Eng. Chem. Anal. Ed. **13**, 1 (1941).
[2] W. H. Avery, J. Opt. Soc. Am. **31**, 633 (1941).
[3] J. R. Nielsen, Oil Gas J. **40**, 34 (1942).
[4] R. R. Brattain and O. Beeck, J. App. Phys. **13**, 699 (1942).
[5] R. B. Barnes, U. Liddel, and V. Z. Williams, Ind. Eng. Chem. Anal. Ed. **15**, 83 (1943).

* Optical density is defined as $D = -\log_{10} T = \log_{10}(I_0/I)$, where T is the transmission, I_0 the energy incident on the sample, and I the energy transmitted by the sample.

densities of the components, or

$$D=d_1+d_2+\cdots+d_n \qquad (1)$$

and the optical density d_n of an individual component can be expressed by

$$d_n=\epsilon_n x_n. \qquad (2)$$

This is the familiar Beer's law where x_n is the mole fraction† and ϵ_n the extinction coefficient (of the nth component) which is a constant for all values of x_n but varies with wave-length. Substitution of Eq. (2) in Eq. (1) gives for the optical density D of a mixture at one wave-length

$$D=\epsilon_1 x_1+\epsilon_2 x_2+\cdots+\epsilon_n x_n. \qquad (3)$$

If the experimental conditions under which optical density is measured are such that both of the above conditions hold, a mixture can be analyzed by the following steps:

1. Determination of the ϵ_n values of each pure component at n different wave-lengths.

2. Measurement of the optical densities of the mixture at these wave-lengths.

3. Solution of the n simultaneous linear equations (one for each wave-length) of the type (3) for the mole fractions x.

No spectrograph or spectrophotometer measures the optical density of a substance for truly monochromatic radiation, although some research instruments approach this sufficiently closely so that the deviations from Beer's law are within the experimental error. Spectrophotometers useful for routine analysis and plant control usually measure the optical density for a wave-length band of comparatively large width. This causes the analytical accuracy obtainable by the above method to be limited by the deviations from Beer's law and not by the experimental accuracy of the spectrophotometer. It has been found possible to improve this accuracy by a method based on the assumption that:

The optical density of a mixture equals the sum of the optical densities of the components even though the optical density of an individual component is not expressible as the product of a constant and the concentration.

The general steps involved in this spectrophotometric method for the analysis of multi-component mixtures are outlined below.

A. Calibration

1. The curve presenting the optical density plotted against mole fraction is determined for each of the n pure components at each of n selected spectral positions. In the general case these curves are not straight lines so that the extinction coefficient ϵ_n of Eq. (2) is not a constant as x_n changes.

2. Using the data of step 1, values of the extinction coefficients are chosen so that the difference terms of step 4 below are reasonably small and the n simultaneous linear equations of the type (3) are solved[6] considering these chosen values to be constants. This gives the mole fraction of each component as a linear function of the optical densities of the mixture measured at the n selected spectral positions:

$$x_j=\gamma_j^{(1)}D^{(1)}+\cdots+\gamma_j^{(n)}D^{(n)}, \qquad (4)$$

where the subscript refers to the component, the superscript to the spectral position, and $\gamma_j^{(n)}$ are numerical constants.

3. The theoretical curve of optical density plotted against mole fraction for each of the components at each spectral position is calculated from Eq. (2) using the extinction coefficients chosen in step (2).

4. The differences between the optical densities calculated in step 3 and the experimental optical densities of step 1 are plotted against mole fraction for each component at each spectral position. The results of the calibration steps 1, 3, and 4 can be used in analyzing for the same component in different mixtures while calibration step 2 has to be done for each particular mixture, but only once for all samples of this mixture.

B. Analysis of Samples

1. The optical densities of the sample are determined at each of the selected spectral positions.

2. Equations (4) are solved arithmetically for the mole fractions using the experimentally determined optical densities D of step 1. These mole fractions are only approximate since the true

† Mole fraction is proportional to concentration and is the ratio of the pressure of a component to the total pressure of sample used at the corresponding spectral position when making an analysis.

[6] The otherwise laborious process of solving this system of relatively high order is greatly shortened by a method described by P. D. Crout, Trans. A. I. E. E. **60**, 1235 (1941).

extinction coefficients were not used in solving for Eqs. (4).

3. The experimental optical density at each spectral position is now corrected to a new value by adding to it the sum of the differences between the true and assumed optical densities for each component at this spectral position. These differences are obtained from the curves of calibration step 4 using the mole fractions from analysis step 2. These corrected optical densities are the values which would have been experimentally determined at each spectral position if the optical density of each component were given by the theoretical curves of calibration step 3.

4. Equations (4) are again solved arithmetically for the mole fractions using the values of optical density D determined in step 3. Steps 3 and 4 are repeated until the values of the mole fractions are constant. For the samples so far analyzed one or two corrections have been sufficient.

If the number of samples containing the same components is not large enough to justify the work involved in calibration steps 2 and 3, a graphical analysis method based on the same fundamental assumption can be used. The experimental curves of optical density plotted against mole fraction (calibration step 1) are determined and the sample is analyzed directly from these curves by successive graphical approximations. The first approximate values of the mole fractions are determined by assuming that the entire optical density at each spectral position is due to the principal absorber at that position. These values of mole fraction are used to subtract the optical densities due to non-principal absorbers from the optical densities measured at each spectral position. Using these corrected optical densities better values of the mole fractions are read from the calibration curves and the process is repeated until the mole fractions are constant. This method is rather laborious, especially for samples with four or more components, since it converges rather slowly, requiring sometimes four or five steps in the approximations. It is, however, the most useful method when only a few samples of the same qualitative composition are to be analyzed.

The effect of overlapping absorptions and slit widths on the accuracy of analyses based on the fundamental assumption of additivity of optical densities is difficult to state precisely. If the true absorption coefficient of only one of the components changes over the slit width, this assumption holds exactly. Because of the cumbersome numerical integrations necessary in using the exact expression[7] the definite conditions under which this assumption is valid have not been calculated. It has been our experience that if the conditions mentioned later (see section on Selection of Spectral Positions and Operating Conditions for Analysis) regarding choice of wavelengths to be used in a given analysis are fulfilled, the assumption will lead to excellent results. This has been shown by comparison of the composition of known samples with the composition derived from spectrophotometric analysis, examples of which will be given later in Table II.

INSTRUMENT

Since the various models of the spectrophotometer used in this work have been described previously[4,8] only a brief description will be given here. The light path is shown in Fig. 1, the spectrophotometer with cover removed in Fig. 2, and the complete analysis unit in Fig. 3. This instrument was designed specifically for use in a

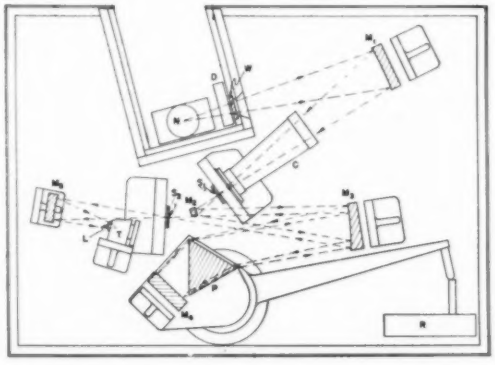

FIG. 1. Light-path diagram of routine infra-red spectrophotometer.

[7] The exact expression for the dependence of the apparent transmission on the true transmission $T(\lambda)$ and spectral slit width s is

$$T_{\text{apparent}}(\lambda_0)=\frac{1}{S^2}\int_{\lambda_0-(S/2)}^{\lambda_0+(S/2)}\int_{\lambda'-(S/2)}^{\lambda'+(S/2)}T(\lambda)d\lambda d\lambda'$$

assuming the incident energy constant over the slit. For a single absorbing gas, with

$$T(\lambda)=e^{-\beta(\lambda)x},$$

where $\beta(\lambda)$ is in general a complicated function of λ, it is seen that T_{apparent} is no longer dependent exponentially on mole fraction, as required for Eq. (3) to be true.

[8] R. R. Brattain, Calif. Oil World **36**, No. 2, 9 (1943); and Petroleum World **40**, 46 (1943).

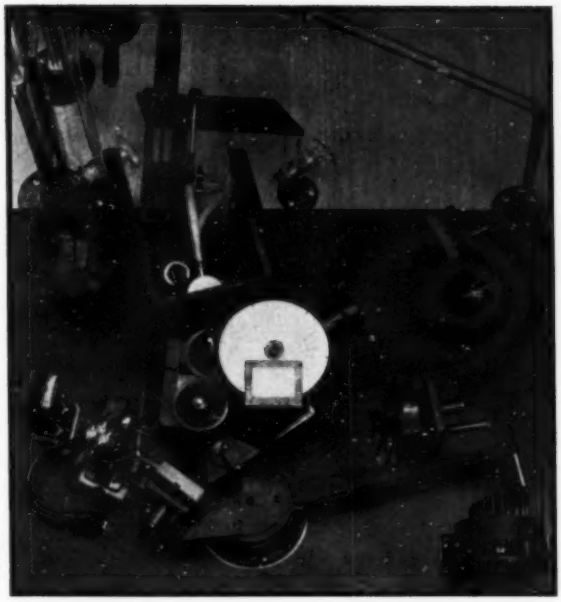

FIG. 2. Routine infra-red spectrophotometer (cover removed).

control laboratory of a manufacturing plant. The turret-stop method of setting wave-lengths was chosen for its good reproducibility at a cost low in comparison with an equally reproducible continuous wave-length setting device. A differential expansion mechanism on the back of mirror M_3 compensates for the temperature change of the refractive index of the prism. Amplification of the energy output of the thermopile would allow the use of narrower slit widths giving closer adherence to Beer's law, but for routine analysis the disadvantages seem to outweigh the advantages. On the other hand, narrower slit widths would require even better temperature correction and wave-length reproducibility. For these reasons and also in order to avoid complications caused by using an amplifier in the comparatively unstable surroundings of a control laboratory only a thermopile and a single galvanometer were used in the present work. However, it should be emphasized that the spectrophotometer itself is not limited to the procedures described in this paper; narrower slits would not necessitate changes in the optical design but merely changes in auxiliary equipment.

ACCURATE TRANSMISSION DATA

As mentioned above the transmission data or optical densities measured must be the true values, if the rule that the optical density of a mixture is equal to the sum of the optical densities of the components is to be successfully applied. The first requirement is that the deflection of the galvanometer be a linear function of the energy striking the thermopile. A well-constructed compensated vacuum thermopile is linear when the energies involved are small as in this case; however, the linearity of the thermopile can be tested by using the inverse square law and a constant radiation source. A deviation from linearity of about 0.2 percent over a deflection of 200 mm at 1 meter is allowable and this standard is not too difficult to attain with a good D'Arsonval type galvanometer. The lateral and angular positions of the coil relative to the pole pieces as well as the curvature and tilt of the scale can be used as adjustments.

The second essential for the measurement of accurate optical densities is that all the energy reaching the thermopile lies in the selected wave-length interval. This selected interval is determined by the spectral slit width and the

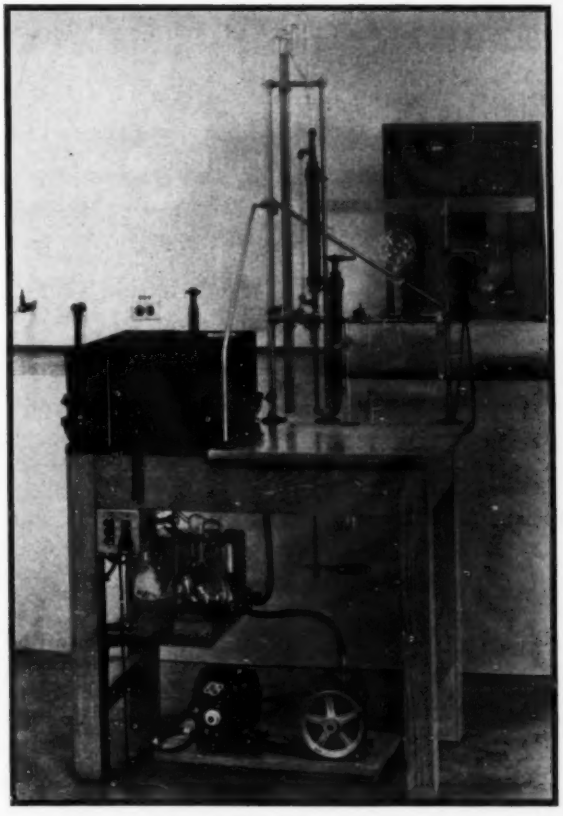

FIG. 3. Complete spectrophotometric analysis unit.

angular setting of the prism. Energy of wave-lengths not in this interval—called false energy—is due principally to scattering from various parts of the instrument. Since the energy peak of the source is around 2μ, the false energy is mostly of short wave-lengths and it interferes most when the spectrophotometer is set for long wave-lengths where the true energy is small and the slit is widest.

Two methods of measuring the true energy are used. A filter of magnesium oxide on a rocksalt plate cuts out most of the energy of wave-lengths shorter than 3μ and transmits about 90 percent of the energy between 3μ and 11μ. Unfortunately, it begins to absorb appreciably past 11μ so that some other method of eliminating false energy must be used at the longer wave-lengths. A shutter of lithium fluoride is used in place of the metal shutter when measurements are made past 10μ. This shutter is transparent to wave-lengths shorter than 7μ and opaque to wave-lengths longer than 9μ. Consequently, short wave-length false energy does not affect deflections taken with this shutter. However, second-order effects, such as the false energy reflected by the LiF shutter and false energy of long wave-length, have to be considered. The exact expression for the transmission of a sample is a complicated function of deflections and false energy but it can be successfully approximated by

$$T=(I-k)/(I_0-k), \tag{5}$$

where T is the transmission, I is the deflection with the gas in the cell, I_0 the deflection with the cell empty, and k is the second-order false energy, which is measured for each spectral position and which is proportional to I_0. Evaluation of k is done by either of two methods:

1. Placing a strongly absorbing gas in the cell at sufficient pressure so that its transmission can be taken as zero; any residual deflection is then k.

2. Selecting the k which gives the most reasonable curve of optical density divided by mole fraction plotted against optical density. The striking effect of k on this curve is illustrated by Fig. 4. As will be explained later the correct k value gives a straight line (in the case illustrated, k is about 2.8). The same basic method of determining false energy has been described[9] before; however, a graphical presentation of optical density plotted against mole fraction was used.

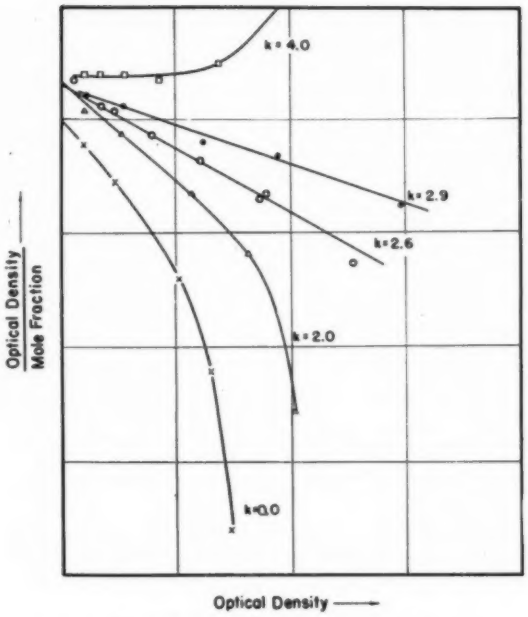

FIG. 4. The effect of second-order false energy.

The amount of gas in the absorption path must be accurately known and, since the absorption is a characteristic of the molecule, this amount must be measured in terms of number of molecules. Since the volume of the absorption cell remains constant, this quantity is most easily measured by pressure, corrected to be proportional to concentration. Since pressures as low as 40 mm are used the pressures should be read to 0.1 mm to insure that pressure errors are not greater than 0.5 percent (0.2 mm). This accuracy is possible with a well-constructed manometer preferably of about 8-mm bore. The pressure read must be corrected for the deviation of vapors from the perfect gas law and for changes of temperature of the sample in terms of changes of temperature of the absorption cell. It has been proven that the temperature of the absorption cell is the same as that of the base plate of the spectrophotometer except for a constant difference. Consequently, it is most convenient to take some base plate temperature as a standard during calibration and correct sample pressures accordingly. The pressure is corrected, using the perfect gas law, to the value necessary to give the same concentration at the standard temperature. For the purpose of the correction necessary be-

[9] M. N. States and J. C. Anderson, J. Opt. Soc. Am. **32**, 659 (1942).

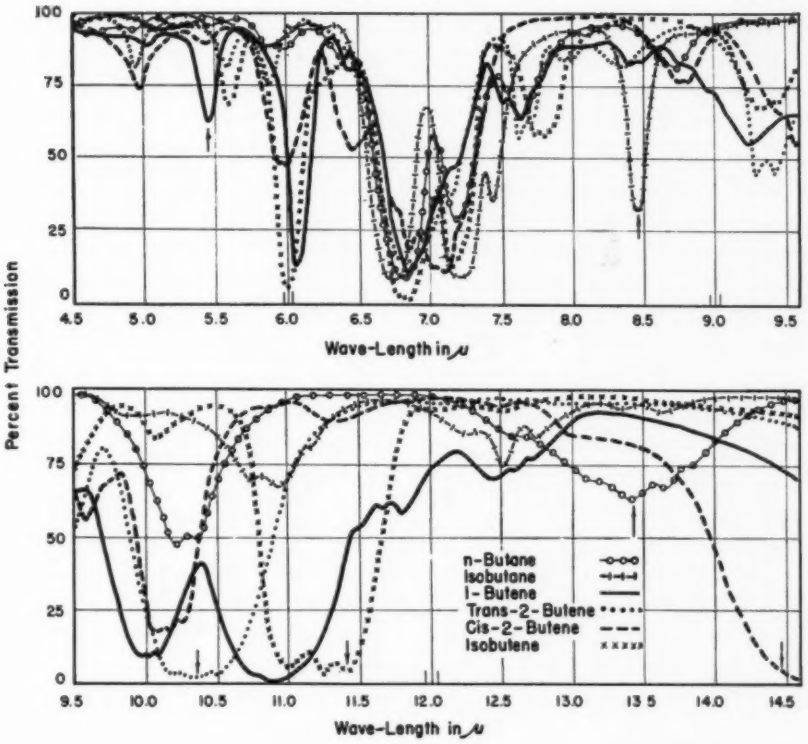

FIG. 5. Composite spectra of a six component C_4 hydrocarbon mixture.

cause of gas law deviation, it is sufficiently accurate to use an average additive value which is the same for all hydrocarbons with the same number of carbon atoms.

A method of testing the reproducibility of the wave-length setting of the spectrophotometer will be described later since it follows directly from the method of selecting the spectral positions at which optical density measurements are made.

SELECTION OF SPECTRAL POSITIONS AND OPERATING CONDITIONS FOR ANALYSIS

The mixture of C_4 hydrocarbons mentioned in the introduction will be used to illustrate the selection of spectral positions at which the optical densities are determined when making an analysis. The spectra of these six compounds are shown superimposed in Fig. 5 and the positions chosen are indicated by arrows. The ideal spectral position would be one at which only one component absorbs and the positions chosen represent in general the closest approach to this ideal. As was explained earlier, it is difficult to state definitely how much interference with the absorption of the principal absorber at a given spectral position can be allowed without seriously impairing the accuracy of analysis based upon the additivity of optical densities. Experience has indicated that the following represent fairly safe limits but not necessarily the ultimate limits:

1. If the absorptions due to the interfering compounds are not changing rapidly (extinction coefficient does not change by a factor of two) over the spectral slit width, up to 50 percent of the absorption of the principal absorber can be tolerated.

2. If the absorptions due to one or more interfering components are changing rapidly and the amounts of these components present are large, the interfering absorption should be limited to 10 percent of the absorption of the principal absorber.

3. If condition No. 2 exists but the amounts of the interfering components present are less than 20 percent, the interfering absorption can be 20 percent of that due to the principal absorber.

Since all the curves used in a composite such as Fig. 5 are for a specific cell length and pressure, such data do not clearly indicate all possible spectral positions. Greater differences of absorption can sometimes be attained by the use of other pressures and the amount of interference is also influenced by the spectral slit width.

In general, the spectral positions chosen are at the absorption maxima of bands of the components. A suitable turret pin is set to the approximate position by using a wave-length calibration and is set to the transmission minimum by determining a small section of the transmission curve of the pure substance. The turret pin is screwed into or out of the turret to traverse the small wave-length interval needed. In other cases, the spectral position may be chosen by determining small sections of the transmission curves of the interfering substances and setting the turret pin to minimum interference. Such a case is illustrated by the position at 10.4μ in Fig. 5 and other cases have been used where the spectral position is on the side of an absorption band of the principal absorber.

The slit width is then set so that the energy deflection is of a size that it is linear and sufficiently large to be read accurately. Within these limits the slit width can be chosen to give minimum interference, which in general means narrow slits with the resulting increase in resolution. However, too small slit widths will make the reproducibility of the instrument insufficient for the analytical accuracy required.

The pressure of sample used at a spectral position is chosen so that this pressure of the principal absorber alone would transmit about 25 percent of the incident energy, since this pressure gives the best average sensitivity. The pressures of sample used at the various spectral positions can be adjusted to increase the accuracy for particular cases. An example where an adjustment should be made would be for samples which consistently contain about 90 percent of one component and small amounts of several others. In such a case the pressure at the spectral position of the principal component should be reduced and the pressures at other positions increased. Since the error in reading the manometer is essentially a constant, not a percentage error, too small a pressure of sample should be avoided.

The operating constants for analyzing the six component mixture of Fig. 5 are summarized in Table I.

A simple and convenient test has been devised for the wave-length reproducibility of the spectrophotometer. This test checks the turret setting and the correction for the change of refractive index with temperature. A turret pin is set to the steepest part on the side of a sharp absorption band of some convenient substance. The absorption due to a standard amount of this substance is then measured at this position with the instrument at different temperatures and with the turret reset between readings. Any failure to reproduce is thus magnified since the ratio of change in percent transmission to change in angular setting of the prism is about ten times greater on the side of a sharp band than it is at the middle of the usual band. A reproducibility of 0.2 percent in the percent transmission used for analysis (i.e., at the bottom of a band) is sufficient.

CALIBRATION

In accordance with the scheme outlined above, calibration curves must be obtained which show the optical densities of the pure gases plotted against mole fraction (at the standard pressure relevant to the wave-length), one such set of curves for each wave-length position. For those cases in which Beer's law holds (absorption coefficient effectively constant over the slit), these curves are straight lines passing through the origin. When Beer's law does not hold, the curves are in general almost straight, but show downward concavity. An illustration of such a set of curves is given in Fig. 6, showing the optical densities of pure 1-butene, cis and trans 2-butene, isobutene, normal butane, and isobutane at 10.4μ, where trans 2-butene is the principal absorber. The standard pressure on which the mole fractions are calculated is 40 mm Hg for this case. The curvature is much more marked in cases where the slit width is of the same order or greater than the width of the band on which it is set, but even in the curves illustrated the curvature is not negligible when an accuracy of ± 0.5 percent (based on total sample) is desired for each component.

TABLE I. Operating constants for C_4 analysis.

Principal absorber	$\lambda(\mu)$	Slit width (mm)	Pressure of sample (mm)	MgO filter	Shutter used	I_0-energy in mm	k of Eq. (5) in mm
1-butene	5.43	0.125	300	in	metal	150	0
isobutane	8.47	0.25	120	in	metal	128	0
trans-2-butene	10.4	0.4	40	in	LiF	126	0
isobutene	11.4	0.5	40	in	LiF	122	0.5
n-butane	13.4	1.1	300	out	LiF	122	2.4
cis-2-butene	14.5	1.5	40	out	LiF	52	2.9

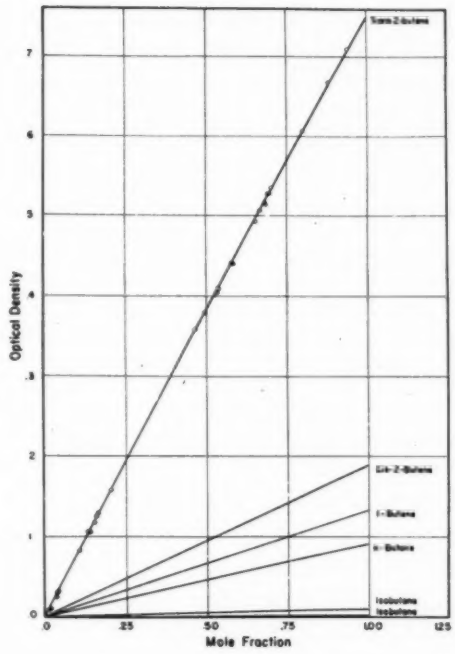

FIG. 6. Graph of optical density against mole fraction for C_4 hydrocarbons at the trans-2-butene band (10.4μ).

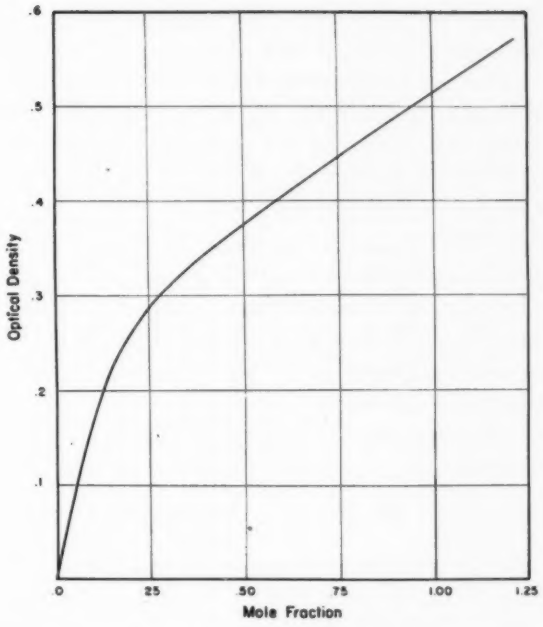

FIG. 7. Example of extreme curvature of optical density-mole fraction curve due to narrow band.

Such calibration curves are obtained by putting the pure gases into the cell at several pressures and measuring the transmission at each. The manometer data read are then corrected as described earlier, and the transmission data are corrected for false energy. At least two such calibration runs are made for each curve to ensure the reproducibility of the values, preferably by different operators and on different days. A further refinement can be made in cases where the small amounts of impurities in the "pure" sample are known from other means of analysis. The pressures of the "pure" gas are then corrected by subtracting the small pressure due to impurity, and the optical densities are corrected by subtracting the optical densities due to impurities. This optical density correction is in some cases rather important; for example, in determining the optical densities of normal butane at the wave-length where isobutane absorbs strongly (8.47μ), the small amount (0.6 percent) of isobutane present in the "pure" normal butane accounts for a large part of the absorption observed.

After correcting for impurities, the pressure values are turned into mole fraction values by dividing by the standard pressure. Since pressures greater than the standard pressure are used in the calibration, mole fractions greater than unity will be obtained, and these are employed to help fix the upper end of the curve. The experimental points of optical density d *versus* mole fraction x are plotted and a smooth curve drawn to fit the points. These curves are then used to analyze unknown samples by either of the two methods described previously.

Actually the calibration curves used in this laboratory are constructed by a modification of the above method. It was found empirically that if d/x is plotted against d for a series of optical densities d and mole fractions x of a pure gas at a given wave-length, the points fall on a rather good straight line. If Beer's law is obeyed, d/x is a constant, and the points fall on a horizontal line; if Beer's law is not obeyed, the line usually has a small negative slope. Since in any case d/x remains fairly constant, the scale in the d/x direction can be made very large, and a more accurate smoothing of the data effected. Assuming that d/x is linear with d,

$$d/x=\epsilon_0+ad \quad \text{and} \quad d=\epsilon_0 x/(1-ax). \qquad (6)$$

This procedure is effectively one of smoothing the

data by fitting them to an analytical curve.* The constants ϵ_0 and a are determined from the *d/x versus d* curve, and the analytical expression (6) is used to calculate the *d versus x* calibration curve. The curves of Fig. 6 were drawn by this method. To check that this curve represents the experimental data, values of d and x are plotted along with the calculated curve, and it is seen that the curve is entirely adequate.

This use of the analytical expression for the *d versus x* curve is particularly helpful in a rapid method for evaluating the difference terms of calibration step 4.

Rewriting Eq. (6) the optical density of a component is

$$d = \epsilon_0 x + \epsilon_0 a x^2/(1-ax). \qquad (7)$$

If the second term on the right is neglected this equation is the same as Eq. (2) and ϵ_0 is used as the extinction coefficient mentioned in calibration step 2. This ϵ_0 is the extinction coefficient extrapolated to zero mole fraction. The second term is then the difference between the true (calibration step 1) and the linear (calibration step 3) curves of optical density plotted against mole fraction. The difference terms of calibration step 4 are thus evaluated directly from Eq. (7) without doing calibration step 3.

If it is desired to construct a working curve for analysis of a two-component mixture by a transmission reading at one wave-length, of the type described in a recent publication,[4] this can be done by adding together the appropriate optical densities of the pure gases, obtained from the calibration curves described above.

Since the exact spectral positions chosen for analysis are arbitrary and since it is difficult to reproduce exactly the same spectral position on two instruments, calibration curves are probably not transferable between spectrophotometers.

ANALYSIS OF SAMPLES

The experimental readings for an analysis of an unknown sample are obtained by setting the prism at the wave-lengths used for the particular analysis, reading the galvanometer deflection with the cell empty and again with the cell filled to the appropriate pressure for each wave-length. The pressure settings need not be exactly the standard pressure required for each wave-length, since this would be too time-consuming, and since the pressure must be corrected for gas law deviation and temperature anyway. Instead, the pressure is set close to the standard pressure (to one or two mm Hg) and in calculating the optical density a suitable correction is applied. This correction is made by assuming that the optical density is linear with the pressure, which, since the correction is small, is justifiable. The optical densities so obtained are then the quantities on which final calculations of composition are made.

If components are present in the sample whose amounts are known by other independent means, the optical density at the various wave-lengths due to these components can be found from the calibration curves and subtracted from the observed densities. This eliminates the necessity of considering these components further in the calculations.

The analysis of a multicomponent sample by this method thus contains four steps after calibration is completed.

1. The optical densities at the selected spectral positions are determined under the standard conditions—as in Table I.

2. The approximate amount of each component present is determined by arithmetically solving Eqs. (4).

3. The experimental optical densities are corrected using the mole fractions of step 2 above and the correction charts of calibration step 4.

4. Equations (4) are resolved for the amounts of each component using the optical densities of step 3 above.

Analyses of a large number of five-component samples have shown that the graphical approximation method took forty minutes, and the method outlined above took fifteen minutes, for the calculation of one sample.

TESTS OF THE METHOD AND ERRORS

The method has been developed and used for analyzing mixtures of isobutane, *n*-butane, 1-butene, trans-2-butene, cis-2-butene, and isobutene. The two forms of 2-butene have different spectra and must be treated as distinct com-

* In cases where the curvature of the *d versus x* curve is extreme, as illustrated in Fig. 7, the plot of *d/x versus d* does not give a straight line, and hence cannot be used for an analytical representation, but may still be of use in smoothing the data.

ponents. The results of check analyses of synthetic samples are shown in Table II. These synthetic samples were mixed from samples of about 99.5 percent purity by measuring the pressure of each component in a fixed volume and correcting the measured pressures for gas law deviations. Corrections were also applied to take account of the small impurities when these were known. The compositions of the gases which were used for calibration and from which most of the synthetic samples were mixed are given in Table III.

The average absolute deviation per component determined (81 individual checks) for the fifteen runs recorded in Table II is 0.23 percent. In general the accuracy of the values is 0.5 percent of the total sample although deviations of 1.0 percent occur infrequently. The piling up of experimental errors usually causes the total to deviate from 100 percent by 1 or 2 percent. If the qualitative composition of the sample is known and all components have been included in the analysis, this error is distributed among the components so that the sum equals 100 percent. The experimental error of 0.5 percent sometimes causes the percentages of components, included in the analytical scheme but absent entirely or present only in traces (0.3 percent), to have small negative values. These are reported as zero.

Small impurities of substances not analyzed for will also cause the total to deviate from 100 percent. If these impurities are other hydrocarbons, they will cause an error of about the same or smaller size than the percentage of the sample they represent. This follows from the fact that the absorption bands of similar hydrocarbons are about equal in intensity and that they usually do not coincide exactly. If the impurities are substances of much weaker absorption, they will make the total low; if of much stronger absorption, they will make the total high and also the percentages of the components with which they interfere high. Due to the normal experimental deviation, it is thus difficult to detect unsuspected impurities present to less than 3 percent or 4 percent.

About eighty-six component C_4 samples have been analyzed by this method and the average time per sample was one hour with a fairly experienced operator. The experimental readings

TABLE II. Comparison of synthetic sample compositions with compositions found by infra-red analysis.

Sample No.	1			2			3			4			5			6			7			8		
	T	*F*	Δ	*T*	*F*	Δ	*T*	*F*	Δ	*T*	*F*	Δ	*T*	*F*	Δ	*T*	*F*	Δ	*T*	*F*	Δ	*T*	*F*	Δ
isobutane							37.7	38.3	0.6	0.1	0.0	0.1	17.5	17.6	0.1	14.0	13.8	0.2	12.0	12.1	0.1	0.0	0.0	0.0
n-butane							21.6	21.4	0.2	14.9	14.9	0.0	34.0	33.8	0.2	14.8	14.0	0.8	0.1	0.0	0.1	4.6	4.2	0.4
1-butene	55.7	55.5	0.2	49.7	49.7	0.0	4.6	4.6	0.0	65.3	66.2	0.9	16.2	15.9	0.3	4.8	5.4	0.6	64.6	64.0	0.6	46.5	46.5	0.0
cis-2-butene	44.3	34.4	0.3	0.0	0.0	0.0	6.1	5.8	0.3	4.5	4.2	0.3	12.0	12.0	0.0	0.0	0.0	0.0	14.4	14.6	0.2	37.0	37.4	0.4
trans-2-butene		9.6			0.0		1.9	1.9	0.0	1.4	0.9	0.5	3.8	3.8	0.0	0.0	0.0	0.0	4.7	4.7	0.0	11.7	11.6	0.1
isobutene	0.0	0.5	0.5	50.3	50.3	0.0	28.0	28.0	0.0	13.8	13.8	0.0	16.9	16.9	0.0	66.4	66.8	0.4	4.1	4.6	0.5	0.0	0.3	0.3
		9			10			11			12			13			14			15				
isobutane	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.6	22.7	0.1	0.0	0.0	0.0	70.8	70.0	0.8	0.0	0.0	0.0			
n-butane	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	7.9	0.4	0.5	0.0	0.5	29.2	28.6	0.6	0.0	0.0	0.0			
1-butene	24.8	24.5	0.3	24.8	24.4	0.4	99.4	99.8	0.4	13.3	13.9	0.6	0.0	0.0	0.0	0.0	0.8	0.8	49.7	49.8	0.1			
cis-2-butene	75.2	54.1	0.3	75.2	54.6	0.4	0.3	0.1	0.2	31.5	21.8	0.5	75.6	77.0	1.4	0.0	0.5	0.5	0.0	0.0	0.0			
trans-2-butene		21.4			21.0		0.3	0.1	0.2		9.2		23.7	23.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0			
isobutene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.3	24.5	0.2	0.0	0.0	0.0	0.0	0.1	0.1	50.3	50.2	0.1			

Note: 1. *T* = true percentage, *F* = found percentage, Δ = absolute value of deviation.
2. This table includes all check runs taken.
3. In samples 1, 2, 9, 10, 12, 15, the true percentages were uncorrected for impurities, since standard samples from which they were mixed were of unknown composition although all better than 99.0 percent.
4. Sample 13 contained 0.2 percent higher boiling.

TABLE III. Compositions of standard C_4 hydrocarbons used in calibration and check samples.

Standard sample	Percentage of: iso-butane	n-butane	1-butene	cis-2-butene	trans-2-butene	iso-butene	higher boiling
isobutane	99.7	0.3	—	—	—	—	—
n-butane	0.6	99.4	—	—	—	—	—
1-butene	—	—	99.4	—	—	0.6	—
cis-2-butene	—	—	—	100.0*	—	—	—
trans-2-butene	—	—	—	—	100.0*	—	—
isobutene	0.2	—	0.15	—	—	99.65	—
mixed 2-butenes**	—	0.5	—	75.6	23.7	—	0.2

* Pure samples obtained from Dr. W. E. Vaughan, prepared at Harvard University. The small amount of these samples precluded any analysis being made to determine their purity but the method of preparation justifies assuming 100 percent. These samples were used for calibration runs only.

** Used for mixing of check samples. Cis- and trans- values were determined by infra-red analysis.

take about forty minutes and the calculations the remaining twenty. An operator should learn the method in three days and should attain the above rate in two or three weeks.

APPLICATIONS AND LIMITATIONS

In principle the method is applicable to any vapor or liquid mixture. However, the difficulty of finding an appropriate spectral position for each component will probably limit the method to mixtures of less than eight or ten components. Applications to liquid mixtures would require cells highly reproducible as to transmission and sample thickness, and a thorough study of the deviations from Beer's law for liquid mixtures. Both of these difficulties would be reduced by using dilute solutions in a transparent solvent.

The principal advantage of the method is its rapidity for routine work with an accuracy at least equal to standard gas-analysis methods such as low temperature distillation. Also, it is the only practical method of performing certain analyses such as distinguishing between the isomers of 2-butene. There is, however, the disadvantage that in general the qualitative composition of a sample must be known. Furthermore, considerable time is consumed in calibration for a mixture with a large number of components although some of the calibration is often usable in analyzing different mixtures with some components in common. Hence, this method is most valuable for the rapid routine analysis of large numbers of samples containing the same components.

ACKNOWLEDGMENTS

We wish to thank Dr. O. Beeck for his encouragement and guidance, Mr. Pierre Zucco for his assistance in obtaining the experimental data, and Mr. B. M. Burchard for his technical assistance in connection with the spectrophotometer.

Radiosulfur Tracer Study of Sulfurized Lubrication Addition Agents

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Radioactive tracer techniques have been used to ascertain the concentration of sulfurized addition agent in lubricating oil blends on metallic surfaces, the active element being radiosulfur prepared with the cyclotron and introduced into the olefin molecules. Film formation seems to be quite general, having been tested on seven different types of commercial metallic bearings as well as on glass. The film is transparent and very thin. In the extreme cases, it imparts a faint opalescence to the bright surface. The organic molecules may form a loose molecular compound with the metal or a polymerized film, sufficiently adherent, however, to resist the solvent action of benzene and carbon disulfide. The rate of film formation has been established at 88°C (190°F) and at room temperature for a typical bearing composition. It has been found that the rate though several times slower than at 88°C at room temperature is still quite appreciable and favorable from the standpoint of engine protection. The mechanism of oxidation inhibition and thus retardation of corrosion and sludging with this addition agent seems to embrace both alteration of surface character of catalyzing metals and bulk or liquid phase inhibition in the oil. The adherent organic film is probably involved in "oiliness" (film strengthening and prevention of complete oil drainage from motor bearings and walls by anchoring through polar molecules) since engine tests have shown that the oiliness of straight mineral oil is appreciably improved by addition of sulfurized olefins.

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INTRODUCTION

FOR several years this laboratory has been engaged in fundamental researches on the action of a variety of polar addition agents blended with ordinary hydrocarbon lubricating oils.[1–7] X-ray and electron diffraction and hydrophil balance measurements have demonstrated the adsorption and preferred molecular orientation of these agents (such as methyl dichlorostearate) at interfaces, thus increasing film strength and anchoring these protective oil films on bearing and cylinder walls. This is the property sometimes called "oiliness"[8–10] which Kalichevsky and Stagner[11] define as "the tenacity with which a given oil is capable of adhering to the metal surface at high bearing pressures."

More recently, sulfur-containing organic compounds have been blended with lubricating oils. Extensive engine tests and commercial experience have proved the value of some of these sulfur compounds in increasing film strength, in inhibiting oil deterioration, and in increasing engine life.[12]

This investigation concerns itself chiefly with the mechanism of inhibiting oil oxidation and the effect on metal surfaces of "Thialkene Inhibitor,"[13] a Continental Oil product made by sulfurizing olefins derived from petroleum wax.

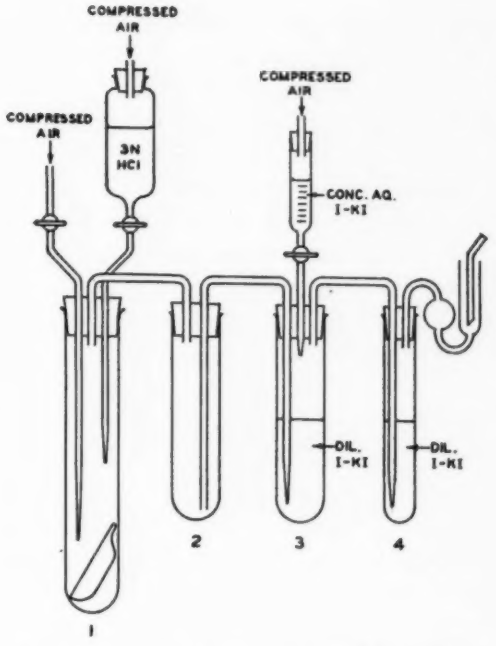


FIG. 1. Apparatus for preparation of sulfur from radioactive barium sulfide.

Davis, Lincoln, Byrkit, and Jones[14] have shown the accelerating effect of metal organic compounds on oil oxidation. It has also been found by Downing, Holbrook, and Fuller[15] and also by Matthijsen[16] that a lubricating oil may deteriorate much faster in contact with metallic parts than when in contact with inert surfaces even though the lubricant in both cases may be subjected to identical treatment. These observations have suggested several possible methods of inhibiting oxidation and thus extending the life of the lubricating oil. A sulfur compound may act as a true oxidation inhibitor by taking up oxygen or neutralizing the accelerating effect of metal organic compounds in the oil; or it may, on the other hand, alter the character of the metal surface and thus minimize its catalytic effect in the oxidation process.

For the study of this sulfur-containing addition agent, a powerful new method immediately suggested itself, namely, the introduction of "tagged" radioactive sulfur atoms into the compound to serve as tracers to show whether there is a con-

[1] G. L. Clark, R. R. Sterrett, and P. W. Leppla, J. Am. Chem. Soc. **57**, 330 (1935).
[2] G. L. Clark, R. R. Sterrett, and B. H. Lincoln, Am. Petr. Inst. Preprint (1935).
[3] G. L. Clark, R. R. Sterrett, and Bert H. Lincoln, privately printed pamphlet (1936).
[4] G. L. Clark, R. R. Sterrett, and Bert H. Lincoln, J. Ind. Eng. Chem. **28**, 1318 (1936).
[5] G. L. Clark and P. W. Leppla, J. Am. Chem. Soc. **58**, 2199 (1936).
[6] G. L. Clark, R. R. Sterrett, and Bert H. Lincoln, *Science of Petroleum* (Oxford University Press, London, 1938), p. 256.
[7] G. L. Clark and J. V. Robinson, J. Am. Chem. Soc. **62**, 1948 (1940).
[8] J. H. Byers, National Petroleum News **29**, No. 28 R3–8 (1937).
[9] L. L. Davis, Bert H. Lincoln, B. E. Sibley, in Dunstan, Nash, and Tizard, *Science of Petroleum* (Oxford University Press, London, 1938), pp. 2673–8.
[10] V. A. Kalichevsky, *Modern Methods of Refining Lubricating Oils* (Reinhold Publishing Corporation, New York, 1938).
[11] V. A. Kalichevsky and B. A. Stagner, *Chemical Refining of Petroleum* (Reinhold Publishing Corporation, New York, 1942).
[12] Frank A. Suess, H. C. Baldwin, W. A. Jones, Bert H. Lincoln, J. Soc. Auto. Eng. **49**, 24 (1941).
[13] "Thialkene Inhibitor," Trademark Registered in United States Patent Office by Continental Oil Company.
[14] L. L. Davis, Bert H. Lincoln, G. D. Byrkit, W. A. Jones, Ind. Eng. Chem. **33**, 339 (1941).
[15] F. B. Downing, G. E. Holbrook, and J. H. Fuller, Oil and Gas Journal **38**, 72, 75 (1939).
[16] H. L. Matthijsen, J. Inst. Petroleum **26**, 79 (1940).

centration of the sulfur-containing organic compound at the metal surface or whether the agent acts as a true oxidation inhibitor or neutralizer of oxidation accelerators in the body of lubricant; and perhaps, in addition, it might throw some light on the formation of oriented layers by these sulfur compounds. The x-ray and electron diffraction methods have detected the presence of adsorbed films although these are essentially amorphous in character so that intermolecular spacings cannot be measured.

MATERIALS AND APPARATUS: RADIOSULFUR FROM RADIO-$BaSO_4$

The radioactive sulfur,[17–20] half-life 88 days, was produced from CCl_4 with the cyclotron at Washington University, St. Louis, Missouri, by means of the following nuclear reaction:

$$_{17}Cl^{35}+{}_0n^1\rightarrow{}_{16}S^{35}+{}_1H^1.$$

The sulfur was furnished in the form of $BaSO_4$. After charring off the filter paper in a platinum boat, the sample and boat were placed in the Alundum tube of a Burrell glow-bar furnace. In this step it was found desirable to place the platinum boat inside a larger porcelain boat for purposes of stability and safety. After initial displacement of the air in the tube with hydrogen, the temperature was raised slowly (45 to 60 minutes) to 1000°C. The furnace was allowed to cool to 600°C and then brought up to 1000°C a second time to insure complete reduction of the sample. During the entire process of heating and cooling, a slow, steady stream of hydrogen was kept flowing through the system. It was found that the frequently recommended single heating to 900°–1000°C produced about 75 percent reduction.

When the entire system had cooled to room temperature, the barium sulfide and boat were introduced into the gas generator shown in Fig. 1. Three-normal hydrochloric acid was added dropwise under pressure and a steady flow of air maintained to sweep the active hydrogen sulfide into a dilute aqueous solution of iodine in potassium iodide.[21]

The supplementary supply of concentrated I-KI solution under pressure was found useful in avoiding a great excess of iodine, which seemed to promote the formation of a gummy mixture of iodine and sulfur. The dilute I-KI solution in tube 4 served as an adequate trap for any hydrogen sulfide that may have escaped the first solution and the lead acetate paper served as a final check of completeness of reaction. Compressed air was bubbled through the excess hydrochloric acid in tube 1 for one hour after all visible evolution of hydrogen sulfide had ceased. Finally the temperature was raised to about 90°C and air passed through for an additional half hour. This treatment served to sweep the last traces of hydrogen sulfide into the I-KI solution.

The slight excess of iodine in both tubes was destroyed by introducing an atmosphere of inert hydrogen sulfide over the solution and shaking. This was found preferable to the more rapid bubbling technique inasmuch as it cut down mechanical loss of the amorphous sulfur. The greater part of the sulfur yield is obtained as a gummy lump, badly contaminated with iodine. It was found, however, that successive digestions in a boiling water bath with intermediate cooling served the twofold purpose of extracting the iodine and converting the sulfur to a more easily handled, granular form. The iodine thus liberated was destroyed by introducing once more an atmosphere of inert hydrogen sulfide. The use of inert H_2S in this way was found permissible since it was desirable that the radioactive sample be somewhat diluted with inert sulfur prior to use.

When the sulfur appeared clean and free of iodine, it was collected on a hardened filter paper by means of a Hirsch funnel and filter flask, washed with distilled water, and dried in a desiccator. The over-all yield was 32 milligrams or approximately 80 percent.

PREPARATION OF ADDITION AGENT

The radioactive sulfur sample was further diluted to 50 milligrams with inert flowers of

[17] R. A. Cooley, D. M. Yost, E. McMillan, J. Am. Chem. Soc. **61**, 2970 (1939).
[18] M. D. Kamen, Phys. Rev. **60**, 540 (1941).
[19] H. Levi, Nature **145**, 588 (1940).
[20] G. T. Seaborg, Chem. Rev. **27**, 199 (1940).
[21] A. E. Wells, Ind. Eng. Chem. **8**, 770 (1916).

sulfur. A quantity (0.397 gram of an olefin (iodine No. 100), made by chlorinating and dehydrochlorinating petroleum wax,[22] was mixed with three times this weight of a solvent-refined neutral oil and heated to 160°C with constant stirring in an oil bath (apparatus shown in Fig. 2).

The sulfur was then added and the temperature raised and held at 180°C for forty minutes, maintaining constant stirring during the entire reaction period. The sulfurization reaction will give compounds clear and free from uncombined sulfur but of varying sulfur stability depending upon the percentage, based on olefin content, of sulfur added and the time and temperature of sulfurization. By varying these factors, it is possible to prepare compounds with controlled chemical activity ranging from those which will discolor rapidly a polished copper strip to those which produce no discoloration. The degree of chemical activity is determined by employing the 212°F copper strip corrosion test[23] on a blend of the refined sulfurized olefin with mineral oil to increase the sulfur content of the mineral oil by 0.15 percent and in some cases by 0.35 percent by weight. A sulfur compound for use with high copper-content bearing materials should be stabilized to a greater degree than if it is to be used on other bearing materials.

Upon completion of the sulfurization, the reaction mixture was cooled to approximately 105°C and 20 percent by weight of Filtrol clay

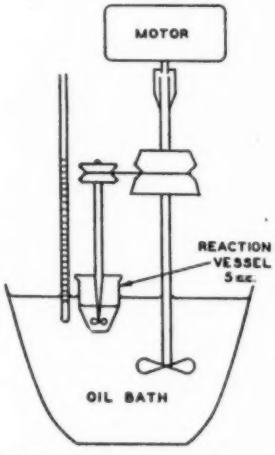


FIG. 2. Apparatus for preparation of sulfurized olefin (0.15 percent sulfur).

[22] Bert H. Lincoln, W. L. Steiner, G. D. Byrkit, U. S. Patent 2,218,132, issued October 15, 1940, and others issued and pending.

[23] Federal Specifications, Method 530.31 (VV-L-791b).

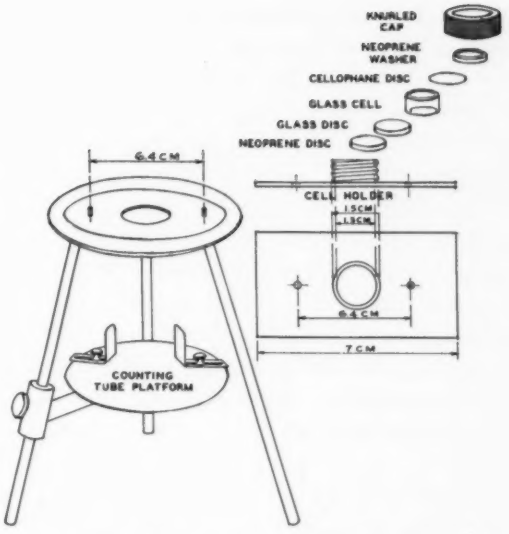


FIG. 3. Cell, holder, and support for measurement of radioactivity.

added carefully with continuous stirring. The temperature was then raised to 120°C and held for ten minutes. The product was filtered into a weighing bottle through a hardened filter paper by means of a Hirsch funnel and a filter flask. The yield was 1.310 grams (approximately 80 percent). This quantity was sufficient to give 26.20 grams of the final blend, containing 0.15 percent added sulfur. The copper strip test for reactive sulfur on the final blend was negative.

THE GEIGER-MÜLLER COUNTER

The counting amplifier was the commercial model, Type A, manufactured by the Cyclotron Specialties Company, Moraga, California. The counting tube used was one of the argon-ethanol, mica-window type, especially sensitive to beta-rays. The tube for the most part is constructed according to directions given by Strong.[24] A mica window of 2–3 mg per sq. cm has been found by other investigators to transmit as much as 60 percent of the weak sulfur betas (energy 0.107 Mev). The reaction taking place in the disintegration is as follows:

$$_{16}S^{35} \rightarrow {}_{17}Cl^{35} + \beta.$$

Figure 3 shows the liquid cell, holder, and support. The cell was found to be particularly

[24] J. Strong, *Procedures in Experimental Physics* (Prentice Hall, New York, 1938).

useful in that it permitted exact reproduction of volumes. The support afforded adjustability as well as the essential feature of reproducible geometry. The cell holder also permitted counts from small metal disks cut out of flattened bearings.

A satisfactory curve for the correction of counting loss was made by means of fifteen samples of carnotite ore and reproducible positions with respect to the counting tube. The sample support used consisted of a small block of wood with fifteen holes drilled through it. The labelled carnotite samples in small test tubes were placed single and in various combinations in their corresponding positions. Great care was exercised to avoid agitation of samples and to place them in exactly the same position each time. The difference between the activities of the various combinations and the sum of the parts represents counting loss. An experimental curve of this sort provides a good approximate correction and is free from the error that may arise from employing only theoretical considerations.

EXPERIMENTAL

Throughout this investigation, measurements were made by either of two techniques. In one, the radioactive oil blend was placed in the glass cell with a medicine dropper and the activity measured through a window of DuPont No. 300 Plain Transparent Cellophane (approximately 0.00088 inch thick). The other method made use of small flat disks cut out of flattened cylindrical bearings which, during the counting, occupied the position of the Neoprene washer in the assembled sample holder.

It was established by a series of determinations that one cellophane disk absorbed 42.6 percent of the beta-rays and two thicknesses 77.3 percent. These disks were used to bring very high counts down within the range of the counting-loss curve. Activities throughout are given with background subtracted. Before all measurements, the metal disks were thoroughly rinsed with benzene. Consequently, all activities recorded for the metallic surfaces are due to a film not soluble in benzene. The films were also found to be insoluble in carbon disulfide.

Specimens 1 to 7 inclusive were immersed in the radio-blend and heated in an oven at 88°C. A small sample of the oil was heated without a metal disk for comparison purposes. Specimens 8 and 9 were the same as specimen 5 and were used to determine the rate of film formation at 88°C and 25°C, respectively. Each specimen, its treatment and measurements, are discussed separately.

Specimen 1—Federal-Mogul Sintered Cu-Pb

A total area of 7.6 sq. cm was exposed to the action of 5.6 cc of radioblend for a period of 24 hours at 88°C and 48 hours at 25°C. The specimen was thoroughly rinsed with benzene and the activity of the extremely thin dark brown to black film on a surface of area 1.54 sq. cm was measured and found too great for the register to record without chattering—probably between 5000 and 10,000 per minute. The color of this extremely active film would lead one to suspect that the sulfurized olefin had not been sufficiently stabilized for this particular type of bearing.

Counts of 385 ± 3 and 339 ± 3 were obtained for the control oil and the residual oil, respectively, indicating a loss in activity of only 12 percent.

Specimen 2—Federal-Mogul Bermax

The area exposed was 7.6 sq. cm, the volume of oil 5.6 cc. The specimen was heated for 24 hours at 88°C and stood at room temperature for 96

TABLE I.

Specimen	Surface	Exp. (hr.) 88°C	Exp. (hr.) 25°C	Counts/min.	Nature of film
1. Fed.-Mogul Sintered Cu-Pb	Copper	24	48	5000	Thin brown to black, Metallic
2. Fed.-Mogul Bermax	85% lead	24	96	104 ± 2	Invisible
3. Cleveland Graphite Microbearing	90% tin	24	120	1100 ± 25	Invisible
4. GM Durex	91% lead	108	48	975 ± 15	Light brown, Transparent
5. Cleveland Graphite Triplate	90% tin	108	48	1130 ± 20	Slightly Opalescent
6. Fed.-Mogul Aluminum	Aluminum	108	48	395 ± 5	Invisible
7. Fed.-Mogul Cd-Ag	Cadmium	86*	48	218 ± 5	Invisible
	Silver	22†	48	670 ± 10	Invisible

* 22 hours additional in contact with bottom of vessel.
† 86 hours additional in contact with bottom of vessel.

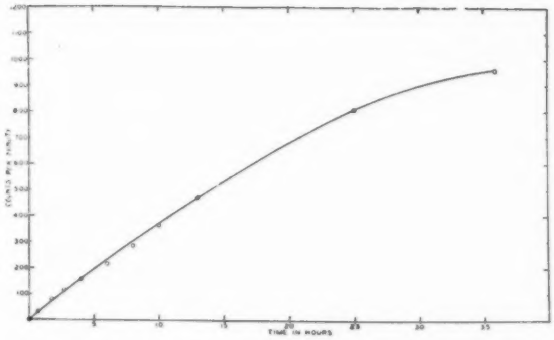


FIG. 4. Typical plot of radioactivity of film on bearing as a function of time of exposure to radioblend at 88°C.

hours. The activity was found to be 104±2. There was no visible evidence of discoloration or tarnish on the bearing surface. The activity was not altered even after repeated rinsing in benzene. No measurement of loss of activity of the oil was undertaken since, on the basis of specimen 1, it could not be expected to exceed 2 or 3 percent.

Specimen 3—Cleveland Graphite Microbearing

The ratio of metal surface to the volume of oil was the same as in the case of specimens 1 and 2. The specimen was heated for 24 hours at 88°C and stood at room temperature for 120 hours. The activity recorded was 1100±25. There was no visible discoloration or tarnishing of the bearing surface and the film was completely insoluble in benzene and in carbon disulfide.

Specimen 4—General Motors Durex

The specimen with an area of 2.2 sq. cm was heated for a period of 108 hours in 1 cc of radioblend at 88°C and was exposed for an additional 48 hours at room temperature. The activity shown at the end of this treatment was 975±15. A dull transparent film had begun to form toward the end of the treatment, though it remained remarkably free of tarnish for more than 80 hours of the heating period.

Specimen 5—Cleveland Graphite Triplate

The treatment for this specimen was identical with the one above and the final count obtained was 1130±20. There was only a faint opalescence on the metal surface at the end of the treatment.

Specimen 6—Federal-Mogul Aluminum

After the same exposure as specimens 4 and 5, a count of 395±5 was obtained. Here again the film formed was not visible to the naked eye.

Specimen 7—Federal Mogul Cadmium-Silver

This specimen received essentially the same treatment as specimens 4, 5, and 6; however, counts were recorded for both sides since it was observed that the silver (outside of the curved bearing) which, during the greater part of the treatment was in contact with the bottom of the vessel, showed a greater tendency toward film formation.

Table I is a tabulation of the results obtained with the various bearing compositions.

Figure 4 shows a plot of film activity *versus* time of exposure of specimen 8 (a duplicate of 5) to the radioblend at 88°C. Before each measurement, the bearing disk was thoroughly rinsed in benzene. This method of washing was tested by dipping an inactive disk into the blend and after rinsing immediately in benzene, measuring the activity. The increase in activity was not greater than the limit of accuracy of the counter.

DISCUSSION

The curve of Fig. 4 is almost straight for the first twenty hours and then begins to level off slowly, becoming practically horizontal after forty hours. Since the activity of the oil decreased less than 5 percent during the whole process, the change in concentration does not appear to be a primary influence in decreasing the slope of the curve. Several samples were used over and over again with fresh metal disks with similar results, indicating that the active film was not produced

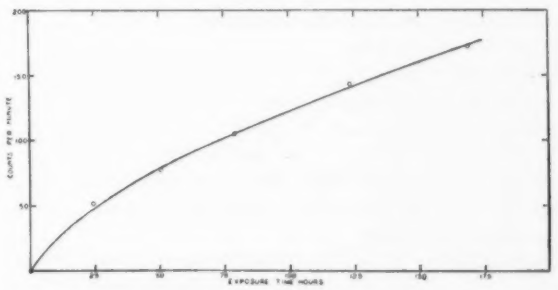


FIG. 5. Typical plot of radioactivity of film on bearing as a function of time of exposure to radioblend at 25°C.

by free sulfur, the absence of which had already been demonstrated by the copper strip test. Figure 5 is a plot of film activity *versus* time of exposure of specimen 9 (a duplicate of 5 and 8) at room temperature. While the film-formation at 25° is slower than at 88°C, this curve is evidence of very considerable protective action.

The phenomenon of film formation was found to take place on glass also. The extremely thin film, which when formed on glass is visible to the eye, formed somewhat more slowly in the containing glass vessel than on metal. The walls of the vessel, after thorough rinsing with benzene and carbon disulfide, showed a remarkably high activity. The actual numerical count had no significance since the geometry of the system was not the same.

Film formation by these sulfurized agents, as in the case of previously studied polar agents, seems to be the result of surface adsorption of somewhat polar molecules from the liquid, which may be accompanied or followed by surface polymerization into an adherent solid film. In any case, the mechanism of surface alteration is indicated as one means of oxidation inhibition.

The quantity of addition agent required to coat the specimens is shown to be considerably less than the optimum quantity employed in commercial practice. Tests performed at the Conoco Laboratories show that there is extensive corrosion of the test equipment and sludge formation when the oil contains less than 0.15 percent added sulfur. This points to the other possible function for the balance of the addition agent, i.e., true oxidation inhibition in the body of the oil. The conclusion, therefore, is that the mechanism of oxidation inhibition by these agents embraces both the bulk effect and the surface conditioning effect produced by film formation.

In addition, the presence of an organic film, whether it be an oriented, adsorbed layer or a polymer has been shown in engine tests to afford some protection at the friction surfaces. Since there is an excess of the film-forming constituent in the oil blend, it seems likely that the film should be self-healing on being injured.

Letters to the Editor

The Early History of the Electron Microscope*

REINHOLD RÜDENBERG
Gordon McKay Professor of Electrical Engineering, Harvard University, Cambridge, Massachusetts
May 27, 1943

I WANT to congratulate Dr. Bachman, his collaborators, and his firm for the success in designing and producing their new handy model of an electron microscope.[1] I know from experience through how many unknown conditions a design often must go which afterwards appears as a matter of course and relatively simple. We must have in mind that in engineering we are accustomed to work with a mechanical accuracy down to say 1/1000 of a centimeter, that optical microscopes have a resolving power of some 1/100,000 of a centimeter, but that electron microscopes are actually working with a precision down to 1/10,000,000 of a centimeter—as of today!

Since Dr. Bachman was kind enough in one of his publications[2] to mention, in connection with the electron microscope, my name as one of the early investigators in this field—for the first time publicly in this country, I think—it may be that your readers will be interested in the manner in which my contribution with respect to the instrument originated.

Stimulated by a case of virus disease in my family and being aware of the discovery of my friend, Hans Busch, that certain magnetic and electric fields in space are capable of concentrating cathode rays in a focus—used at that time for a sharper luminous spot on a fluorescent screen—I recognized late in 1930 the possibility of making use of electrons for producing largely magnified images of small objects, with the purpose of advancing into the domain of viruses. Subsequently I realized that electrons can be caused to produce a real image of a physical object, forming a true pattern of its contrasts, and that such electronic image can be magnified further by repeated application of electromagnetic fields, shaped to act like a lens. This was partly an analogy to the use of optical microscopes and similar magnifying instruments, but with due emphasis on the inherent properties of electrons as different from light waves.

Predominantly, while the power of resolution of light microscopes, according to Helmholtz and Abbé, is limited by the magnitude of the wave-length of the light used, it appeared possible to me with application of electron rays to penetrate deep into the details of the submicroscopic world. For, electrons as imaging agents have a diameter of less than 10^{-12} centimeter and, according to the quantum theory, even their related wave-length is of the order of 10^{-9} centimeter, while light waves are giants of 10^{-5} centimeter.

Since already the first investigations turned out to be very promising, the principal results were expressed in patent applications assigned to the German industrial firm with which I was formerly connected. From the scientific standpoint such patents merely rest a fairly long time until their publication in print, and so the first printing appeared late in 1932 in France. Thus, since the scientific periodicals do not contain these publications,[3] although they have

inherently the earliest priority, I would like to present some of the scientific contents of the respective United States patents, which were printed only in 1936 and 1937, although with priority of May, 1931 (Nos. 2,058,914 and 2,070,319).

The first 3 excerpts from patent No. 2,058,914 show some diagrams and portions of the text in which the general principle of electron microscopy is explained, consisting in the application of concentric field lenses in order to render an electron beam convergent, or divergent, and arranging of such magnetic or electric lenses analogous to optical instruments. Furthermore, the quantitative condition of spatial fields for perfect electronic lens formation is presented, namely proportionality of the radial field strength to the distance from the axis. In addition, there is presented the condition for correct image formation of a physical object by electronic converging as well as diverging lenses, to be used for transmitted or for reflected electron rays.

The fourth excerpt shows a complete electron microscope, as revealed in the above patent, with magnification of the image in a number of steps by use of several field lenses in series, and shows further details for objects which cannot stand the high vacuum. The text explains that the limitation of the resolution, with electrons and their waves, is extended far beyond the wave-length of optical light. The fifth excerpt shows the combination of electronic and optical magnification, enabling the electron beam to perform its main objective under the most favorable conditions, namely, the resolution of the minute submicroscopic pattern of the object to a pattern visible by light, and leaving the subsequent magnification to the optical microscope with its high qualities, developed over the centuries for this purpose.

Finally, taken from Patent No. 2,070,319, the sixth excerpt shows, by using pairs of electrodes, the design of neutral electron lenses which have no secondary stray effects on the beam and are restricted to a local action in space. They constitute a lumped electron field lens without interfering with the axial velocity of the beam, advantageous for a neat design.

The development of the electron microscope was continued by other investigators within and without the corporation mentioned above and its affiliated firms, and has led to great success. Your readers probably know that in Naziland no credit is given to inventors who emigrate.

I am very glad that this country has taken up the production of such instruments with full energy. I am firmly convinced that electron microscopy will bring us a wealth of new significant knowledge in numerous domains as yet uncultivated.

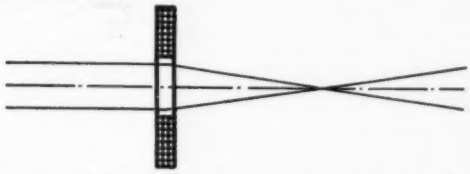
Excerpts from U. S. Patent No. 2,058,914

Issued on Oct. 27, 1936, for an Apparatus for Producing Images of Objects, to Reinhold Rüdenberg, Berlin-Grunewald, Germany, assignor to Siemens-Schuckertwerke Aktiengesellschaft, Berlin-Siemensstadt, Germany, a corporation of Germany.

(Application May 27, 1932, Serial No. 613,857
In Germany May 30, 1931.)

EXCERPT 1. General principle of electron microscope.

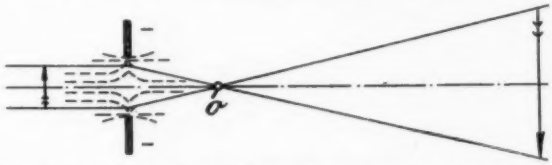
According to my invention, the effect, similar to that of lenses in optics, produced by fields of force surrounding concentrically a beam of electrons and exerting a radial influence on same, is utilized for enlarging objects in a manner corresponding to that obtained with optical magnifying glasses and microscopes. For this purpose the object to be enlarged is exposed to an electron ray or a beam of rays, and before or behind the object, the beam is by means of lens-like acting fields made convergent or divergent.



The principles of optics can, therefore, to a wide extent be applied to arrangements effecting by means of electron rays a magnification of an object to be observed. This applies to the electrostatically acting arrangements described in the examples as well as to arrangements with magnetic convergence and divergence fields.

EXCERPT 2. Condition for lens-forming fields.

When the electrons of a beam or bundle of cathode rays pass through the stop they are repelled by same. They are, therefore, deflected from their original paths, which are assumed to be parallel, towards the center and are assembled to a convergent beam meeting in the focal point 0, beyond which they then diverge. As the radial component of the field strength of the stop is zero in its axis and increases outwardly in linear proportion to the distance, the degree of deflection of the



electron rays also increases with the distance from the beam and stop axis. This causes all the rays to meet in the same focal spot. To obtain with sufficient accuracy this proportional relation of the radial field strength to the distance from the axis, it is advisable to make the opening of the stop considerably larger than the diameter of the original beam, or, by choosing a special shape for the electrodes, to give the field the suitable shape.

EXCERPT 3. Condition for image formation.

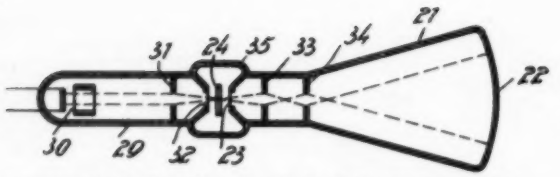
If the potential of the diaphragm is assumed to be positive instead of negative, the electron rays will be attracted by the stop. The rays of the beam which till then were moving in parallel paths now become divergent, as shown above. The negative stop, therefore, has the same effect as a convex lens in optics, and the positive stop has that of a concave lens. By combining stops of that kind, all the devices known in optics and based on converging or diverging beams can be imitated for electron rays. It is in this manner possible, for example, to make a microscope or a telescope for use with direct or reflected electron rays, by proportioning the relative distances between the object, the diaphragm or stop, and the projection screen in accordance with the general optical formula

$$\frac{1}{a}+\frac{1}{b}=\frac{1}{f},$$

in which a represents the distance between the object and the lens (in this case the diaphragm), b the distance between the lens and the screen, and f the focal length of the lens (in the present case the distance at which the charged diaphragm brings the parallel beam to a focal point).

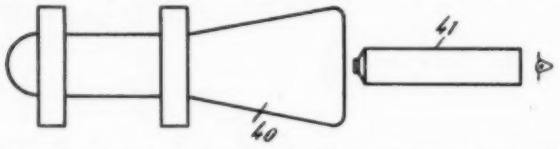
EXCERPT 4. Complete electron-microscope with extended limitation of resolution.

Magnifiers, microscopes, and telescopes constructed in this manner enable observations to be made which are impossible with optical investigations and also permit, regarding the order of magnitude, a considerably greater enlargement to be obtained than is possible with optical instruments, whose resolving power is limited by the wave-length of light. This limitation does not exist with magnifiers operating with electron rays, as the wave-length of these rays is several orders of magnitude smaller than that of light.



EXCERPT 5. Multiplication of optical and electron magnification.

Owing to the imperfection of the lens-effect of the magnetic and electric fields, it is often very difficult to increase the magnification beyond a certain number of times, which is, of the order of the lower powers of ten. In that case the magnification can be carried out in two steps, by employing an optical microscope in addition to the electron microscope. An arrangement of that kind is illustrated below. The electron-microscope is indicated by 40 and the optical microscope by 41.

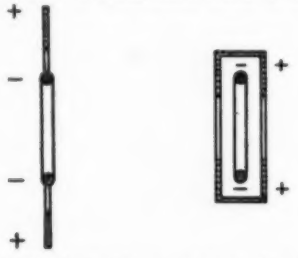


The image produced on the screen of the electron-microscope is enlarged to a size easily attainable with electron rays, and has, for example, a magnification of the order of 100 times the original size after which the optical microscope 41 may easily continue the enlargement.

Excerpt from U. S. Patent No. 2,070,319

EXCERPT 6. Design of neutral electrostatic lenses.

By combining the ring with the disk-diaphragm, as shown, the two being similarly or contrarily charged or only having a difference in voltage, the course of the field can be varied in the effective deflecting zone. A similar variation is also obtained by means of a combination of a circular ring with a surrounding differently charged casing, as shown. To obtain a sharp lens- or focus-effect, forms of electrodes or dia-



phragms with edges forming such curves are employed that their effect upon the electron beam passing through them only takes place within a narrowly limited zone, and that within that zone the radial field strength is as proportional as possible to the distance from the axis, whilst the axial field strength to the right and left of the diaphragm is symmetrical in its course, in order that the additional axial acceleration and retardation of the electrons cancel each other in their effect.

* Given as a discussion to a paper, "Electron Microscope," read by C. H. Bachman at the Technical Meeting of the A.I.E.E. on April 9, 1943 at Pittsfield, Massachusetts.

[1] C. H. Bachman and S. Ramo, J. App. Phys. **14**, 8, 69, 155 (1943).
[2] Reference 1, p. 77.
[3] Except a short reference in Naturwiss. **20**, 522 (1932) by myself.

Ploughing and Adhesion of Sliding Metals

J. J. BIKERMAN
London, England
June 10, 1943

THE reading of the interesting recent paper by Bowden, Moore, and Tabor[1] may be facilitated if the difference between the authors' nomenclature and that generally employed, is pointed out.

The authors speak of "ploughing and adhesion" when obviously scratching and friction are meant. What they measure, is scratch hardness or a parameter of scratch hardness. They use the method introduced by R. Franz[2] and find that the force required to draw the scratching tool over the specimen depends on the shape of the tool, on the friction between tool and specimen, and on the thickness of the specimen if the specimen is a thin film deposited on another material. The effects of all these variables on the measurement of scratch hardness have already been studied (see, e.g., O'Neill[3] and Williams[4]), and it is to be regretted that the authors fail to mention earlier investigations and to specify the progress achieved in their work.

In this connection a paper by Skryabin[5] may also be mentioned; in it the force required to drive a hard pole into a soft material is treated as the sum of a force overcoming the cohesion of the material and of the (inverse) frictional force, much in the same way as done by Bowden, Moore, and Tabor.

The term *friction* appears to be used in their paper in two different meanings. Coulomb's (or Amonton's) law applies to sliding which does not produce a permanent deformation of the bodies in contact; it is, of course, not applicable to scratching (see a more detailed discussion of this point in reference 6). When speaking of Coulomb's law the authors use the term friction in Coulomb's sense, but then, when describing their experiments, the same word is used for what really is resistance to scratching. In this way an apparent disagreement with Coulomb's law is created.

It is difficult to decide whether the authors employ the term *welding* in the usual sense which implies melting and subsequent solidification of two bodies in contact. The photomicrographs reproduced in the paper do not suggest any melting. Unfortunately no attempt appears to be made to prove that there really was a welding.

A lesser point may be mentioned here as well. It is not clear, whether Eqs. (1) and (3) are mutually consistent. In Eq. (1) "A is the projected area of contact," i.e., $\pi rh[2-(h/r)]$, if h is the depth of indentation. It is assumed to be proportional to the applied load W, i.e., $(h/r)[2-(h/r)]=kW$, k being a constant. Hence $h/r=1-(1-kW)^{\frac{1}{2}}$. In Eq. (3) A is the geometrical area of contact between a hard sphere and a soft support, i.e., the surface area of a spherical segment, i.e., $2\pi rh$. It is evidently proportional to $1-(1-kW)^{\frac{1}{2}}$ and not to W as Eqs. (1) and (3) would suggest.

[1] J. App. Phys. **14**, 80 (1943).
[2] R. Franz, Pogg. Ann. **20**, 37 (1850).
[3] H. O'Neill, *The Hardness of Metals and Its Measurement* (London, 1934), pp. 136–168.
[4] S. R. Williams, *Hardness and Hardness Measurements* (Cleveland, 1942), pp. 79–139.
[5] A. K. Skryabin, Colloid J. (Russian) **4**, 255 (1938); C. A. **33**, 2015.
[6] J. J. Bikerman, Phil. Mag. [7] **32**, 67 (1941).

Erratum: Proposal for the Extension of Our System of Mensuration

[J. App. Phys. **14**, 196 (1943)]

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ON page 198 of the above Letter to the Editor, in column 2, line 4, the word "bottom" should read *right;* on line 6, the word "above" should read *to the left of.*